Light Duty Gasoline PM: Characterization of High Emitters and Valuation of Repairs for Emission Reduction

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Disclaimer

The statements and conclusions in this report are those of the contractor and not necessarily those of California Air Resources Board.

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Abstract

As PM emissions from diesel engines continue to be reduced, PM emissions from light duty gasoline vehicles (LDGV) could contribute an increasingly large fraction of remaining on-road PM emissions. While emissions from new vehicles are expected to be very low, worn or malfunctioning vehicles could have PM emissions orders of magnitude higher than normal, well-maintained vehicles. A relatively small fraction of such vehicles could contribute a relatively large fraction of PM emissions.

The current Smog Check program in California does not include a direct measurement of PM, but will include a check for visible smoke starting in January of 2008. The absence of PM data from Smog Checks means that we do not have a statistical distribution of PM emission data for the on-road fleet, nor an estimate for the frequency of occurrence of high PM emitters.

The objectives of this program are to

- Evaluate new methods for identification and possible quantification of high PM emitters, including remote sensing device (RSD) checks and quick checks feasible for use in an I/M environment.
- Recruit at range of high PM emitting vehicles.
- Quantify the PM emissions of the recruited vehicles.
- Relate the PM emissions to the RSD and I/M quick check measurements.
- Quantify the costs and emission benefits of repairing the recruited high emitters.

The results of the program identified several promising tools to provide the ARB with the capability to identify high-PM emitters and to pursue cost effective emission reduction strategies. The tools are applicable in three areas: Remote Sensing Devices for PM to monitor on-road fleet traffic; tailpipe PM instruments to augment Smog Check testing; and dilution tunnel PM instruments to augment compliance testing.

Executive Summary

Light duty gasoline vehicles (LDGVs) could become dominant producers of on-road PM emissions due to the enormous disparity in activity levels for light duty vehicles compared with diesel vehicles. The 2005 statewide California emission inventory predicts 40% of the on-road exhaust emissions from mobile sources are from LDGVs. Since the new regulations require a 90% reduction of PM emissions from heavy duty diesel engine exhaust effective 2007, characterizing and reducing PM emissions from LDGV exhaust will become increasingly important. Older gasoline vehicles and very worn or malfunctioning vehicles can emit PM ten to one hundred or more times as much as a new vehicle. There has been no requirement for PM measurement in the vehicle inspection and maintenance (I/M) program. A check for visible smoke will be implemented in January of 2008. However, while it is a good first step to eliminate the grossest emitters, it is subject to some drawbacks: some high PM emitters do not emit visible smoke; visible smoke levels are not well correlated with PM emission levels; it could be difficult to eliminate subjectivity from procedures to determine visible smoke. Therefore, it is desirable to develop instrumental methods that can identify high PM emitters directly.

The overall objectives of this program are to improve the ability of the ARB to identify high PM emitters and to provide the data on emission levels, repair effectiveness and repair costs for high emitters to guide development of PM control strategies. A total of eight vehicles were recruited and tested for this program. All the vehicles were initially tested in a commercial Smog Check station. The Smog Check data were augmented with particulate emissions measured using a high PM emitter tailpipe screening device (TSD) developed by CE-CERT. The TSD was used during the Smog Check ASM tests as well as during a two speed idle test. These vehicles were then tested over the Unified Cycle (UC) using standard laboratory dynamometer methods. Gas phase and particulate emissions were measured. Remote sensing devices (RSD) measurements using two different systems were conducted for all the vehicles. Approximately one year after repair, three vehicles were repaired and were retested in the laboratory as well as in the Smog Check station.

All the visible smokers have HC and CO emissions over the UC cycle that are relatively high compared to the FTP Tier 1 standard. HC emissions for the visible smokers range from 2.5 to 23.5 g/mi. CO emissions for these vehicles range from 39 to 138 g/mi. The emissions of invisible smokers are all higher than the FTP standards, but not to levels that would represent high emitters, especially considering the more aggressive UC. Some smoking vehicles have relatively low NOx emissions probably due to operating under a rich-burn condition. The PM emission rates of the visibly smoking vehicles range from 60 to 1718 mg/mi. One invisible smoker has a PM emission of 25 mg/mi, which is about 4 times higher than that of the other invisible smoker. The smoking vehicles showed particle number rates on the order of 10^{13}~10^{14} particles/mi, which are 10~1000 times higher than the FTP particle number emission rates of modern low emitting gasoline vehicles. CO_2 emissions of the baseline vehicle operated with maximum AC over the UC cycle for bag 2 and 3 were 25% and 33% higher than the tests without AC. CH_4 and NOx emissions were both increased while NMHC were decreased in both phase 2 and phase 3 with the AC use.

The smog check results for the test vehicles showed that not all the smoking vehicles could be screened by the current Smog Check program. Adding a PM measurement to the Smog Check program could identify some high PM emitting vehicles that would otherwise pass through the program. The TSD can separate the normal PM emitters and the high PM emitters over both the idle/high speed idle and ASM tests.

Five vehicles were sent to dealers for diagnosis and repair estimate. Two vehicles required repairs in excess of $5,000 and were not repaired. The other three vehicles were repaired, and repair costs ranged from $1,700 to $2,200. The three repaired vehicles were retested approximately one year after repairs. Two vehicles had PM emissions much reduced compared to their pre-repair state. One vehicle still had high PM emissions.

RSD measurements at the test track showed that vehicles having higher emission rates over the UC tests generally showed higher emissions as measured by RSD for the gaseous species. For PM, both the ESP UV transmissometer method and the DRI UV backscatter method showed positive correlation with UC PM measurements and were more sensitive than the ESP IR method. The ESP UV method was able to detect both Blue and Black smokers with good sensitivity, while the DRI UV method had reduced sensitivity for Black smokers and the ESP IR method had reduced sensitivity for Blue smokers. All methods showed increased noise if a leading vehicle was followed too closely.

Remote measurements made at the freeway onramp site showed that both systems are able to operate for long periods of time and collect thousands of records per day. The support equipment and personnel required to deploy the DRI system is much more extensive than support equipment and personnel needed to deploy the ESP system. The two systems showed good correlation for gas phase measurements, but little correlation for PM measurements eve for vehicle identified as high PM emitters by ones system or the other.

1.0 Introduction

Associations between ambient particulate matter (PM) and adverse health effects have been well documented in numerous studies [1, 2, 3, 4]. Diesel engines are currently estimated to be primary contributors to the PM emission inventory. The California Air Resources Board (CARB, or ARB) designated PM emitted from diesel engines as a Toxic Air Contaminant (TAC) in 1998. Diesel PM has since received special attention by air quality agencies charged with reducing the public's risk from this pollutant. The most recent EPA and ARB regulations aimed at reducing the publics' exposure to this TAC are applicable to 2007 and new engines, and will require heavy duty diesel engines to be certified to a PM emission standard of 0.01 g/bhp-hr, a 90% reduction. The 2007 regulations require phase in for new engines to be fully implemented by 2010. While the on-road diesel fleet will take many years to turn over, there should be steady progress toward the goal of a 90% reduction in diesel PM emissions.

Emissions of PM from LDGVs should also experience reductions with the introduction of the newest technologies as the fleet turns over. Under the LEV II regulations as revised November 15, 2001, both gasoline and diesel light duty vehicles must meet a PM emission standard of 0.01 g/mile. Even if all light duty vehicles emitted at the level of the LEV II standard, they could still become dominant producers of on-road PM emissions due to the enormous disparity in activity levels for light duty vehicles compared with diesel vehicles. The 2005 California emission inventory predicts 58% of the on-road mobile source emissions are from LDGVs [5]. The Department of Energy (DOE)'s Gasoline/Diesel PM Split Study in the South Coast Air Basin concluded: "Gasoline PM emissions are more important than diesel PM to ambient PM concentrations at certain times and locations. High-emitting gasoline vehicles are very important contributor to ambient PM." [6] Therefore characterizing and reducing PM emissions from LDGVs will become increasingly important.

In practice, most LDGVs do not emit as much as the LEV II standard. Most new LEV II and newer vehicles emit well below the standard. (Emission inventories start with a base rate of less than half the LEV II standard for LEV I and newer vehicles). However, older gasoline vehicles were not required to meet a PM standard and may emit substantially more than the new LEV II standard. Also, very worn or malfunctioning vehicles can emit tens to hundreds of times as much as a new vehicle. Data on the frequency of such high PM emitting vehicles and on the PM emissions rate distribution for such vehicles are limited.

PM emissions of smoking LDGVs have been investigated in several studies in the 1990's [7, 8, 9, 10] as well as the latest DOE Gasoline/Diesel PM Split Study [11]. The average PM emission rates from these studies were found to be in the range of 100-600 mg/mi with the maximum higher than 2000 mg/mi. In contrast, several studies have shown that the PM emissions of normal emitting LDGVs are less than 5 mg/mi [12, 13, 14], with those of the latest technology vehicles at around 1 mg/mi or less [15].

Studies that examine high PM emitters find a poor correlation between high PM emission rates and surrogates such as high HC, high CO, visible smoke, vehicle age, or vehicle mileage [16]. Therefore, it is necessary to develop methods that can identify high PM emitters directly. Remote Sensing Devices (RSD) and new Smog Check methods offer potential to screen very large numbers of vehicles to identify high PM emitters. Remote sensing measurements of PM were made in several studies [17, 18, 19, 20]. An earlier Coordinating Research Council (CRC) study (Project No. E-56) indicated that more work was needed for the development of remote sensing measurements of PM [20].

The overall objectives of this program were to improve the ability of the ARB to identify high PM emitters and to provide data on emission levels, repair effectiveness and repair costs for high emitters to guide development of PM control strategies. A total of eight vehicles were recruited and tested for this program. All the vehicles were initially tested in a commercial Smog Check station. Particulate emissions were measured using a high PM emitter Tailpipe Screening Device (TSD), which was developed by CE-CERT. The tailpipe screening for PM was done during the Smog Check tests as well as during idle/high speed idle modes. These vehicles were then tested over the Unified Cycle (UC) using standard laboratory dynamometer methods. Gas phase and particulate emissions were measured for each test. Estimates to repair five of the vehicles were obtained. Three of the vehicles were repaired and were retested approximately one year after repair in the laboratory as well as at the smog station. Remote sensing measurements for each vehicle were made at a test track using two different systems for comparison with the emission mass measurements. Real traffic meaurements of more than 4000 vehicles were also made with each of the two RSD systems. These measurements provide a gauge of the technology improvements for PM remote sensing over the past several years.

2.0 Experimental Procedures

2.1 Test Vehicles

A total of eight vehicles were recruited for this program. The fleet included vehicles with PM emission levels ranging from baseline to heavy smoking. Prior to entering the program, all vehicles were inspected using a standard checklist to ensure that they were in reasonable mechanical and operational condition. All vehicles were tested with the gasoline in the tank (California RFG) at the time the vehicle was procured for testing in order to represent the real-world in-use conditions. The specific details of the vehicles used in this project are listed in Table 1 along with smoke levels. The expected PM ranges in the table are for emissions weighted in a manner analogous to FTP weighting.

The vehicle test matrix was designed to provide vehicles with different levels of PM emissions and with different types of PM characteristics (i.e., blue or black smoke). This distribution was selected to provide a range of measurement conditions for the RSD PM measurements. The distribution is not designed to be representative of the larger on road vehicle fleet, but rather for specific PM characteristics. The 1963 Studebaker Avanti, selected for its heavy blue smoke, is not at all representative of any on-road technology in the current fleet. Vehicles were prescreened visually and using the TSD prior to inclusion in the program. Vehicles classified as moderate emitters or “invisible” smokers did not have visible smoke during normal running, but did have a noticeable PM signature as measured by the TSD, and did emit a short puff of visible smoke during startup. Vehicles were recruited through newspaper advertisement and the University of California, Riverside campus mail system.

Table 1. Description of Test Vehicles

#	MY	OEM	Model	Type	Disp.	Mileage	Description	Expected PM Range (mg/mi)
1	1997	Ford	Escort	PC	2.0 L	25,598	Baseline	< 5
2	1985	Toyota	Camry	LDT	2.0 L	268,423	Moderate emitter, no visible smoke	25 to 75
3	1991	GMC	Sonoma	LDT	4.3 L	171,487	Moderate emitter, no visible smoke	25 to 75
4	1981	Toyota	Pickup	LDT	2.4 L	119, 728	Blue Smoker, Light	50 to 500
5	1995	Dodge	Dakota	LDT	2.5 L	123,974	Black Smoker, Light	50 to 500
6	1963	Studebaker	Avanti	PC	4.6 L	6.5	Blue Smoker, Heavy	50 to 500
7	1998	Toyota	Camry	PC	3.0 L	82,704	Black Smoker, Heavy	50 to 500
8	1986	Mitsubishi	Max	LDT	2.0 L	163,913	Grey Smoker	

PC = Passenger Car; LDT = Light-Duty Truck. The odometer of the 1963 Studebaker Avanti had been reset and did not represent the actual vehicle miles traveled.

2.2 General Procedures

The procedures of this program are provided in the flowchart in Figure 1 and are briefly summarized below.

- An Acceleration Simulation Mode (ASM) test along with an idle/high speed idle test was conducted for each vehicle at a local Smog Check station. The PM emissions were simultaneously measured with the TSD. The test was conducted in duplicate.

- PM and gas-phase emissions from these vehicles were measured over the UC cycle, with duplicate tests on each vehicle.

- Remote sensing tests on the recruited vehicles were then conducted in the CE-CERT parking lot. Remote Sensing Devices (RSDs) from the Desert Research Institute (DRI) and Environmental Systems Products Holdings Inc. (ESP) were both used in the study.

- The remote sensing equipment was also evaluated for an on-road vehicle fleet at a freeway onramp (not the recruited vehicles). Over 4,000 vehicles were measured by each system. The primary purpose of the test was to evaluate the logistics of setting up the equipment and its general ability to find high PM emitters in the on-road fleet.

- A subset of the recruited vehicles were taken for diagnosis and repair at local repair facilities. Five vehicles were taken for estimates, and three were subsequently repaired. The other two repair-estimates exceed the maximum limit of $2,000, and thus were not repaired. The $2000 limit is reasonable in terms of incentive to repair, and is also reasonable in relation repair waiver or vehicle scrap program amounts.

- Vehicles that were repaired and the baseline vehicle were retested using standard laboratory dynamometer methods and at Smog Check stations, with duplicate tests on each vehicle, approximately one year after repair. Two un-repaired smokers were retested at the same time as the repaired vehicles under another program. The results from those two vehicles are reported here as well.

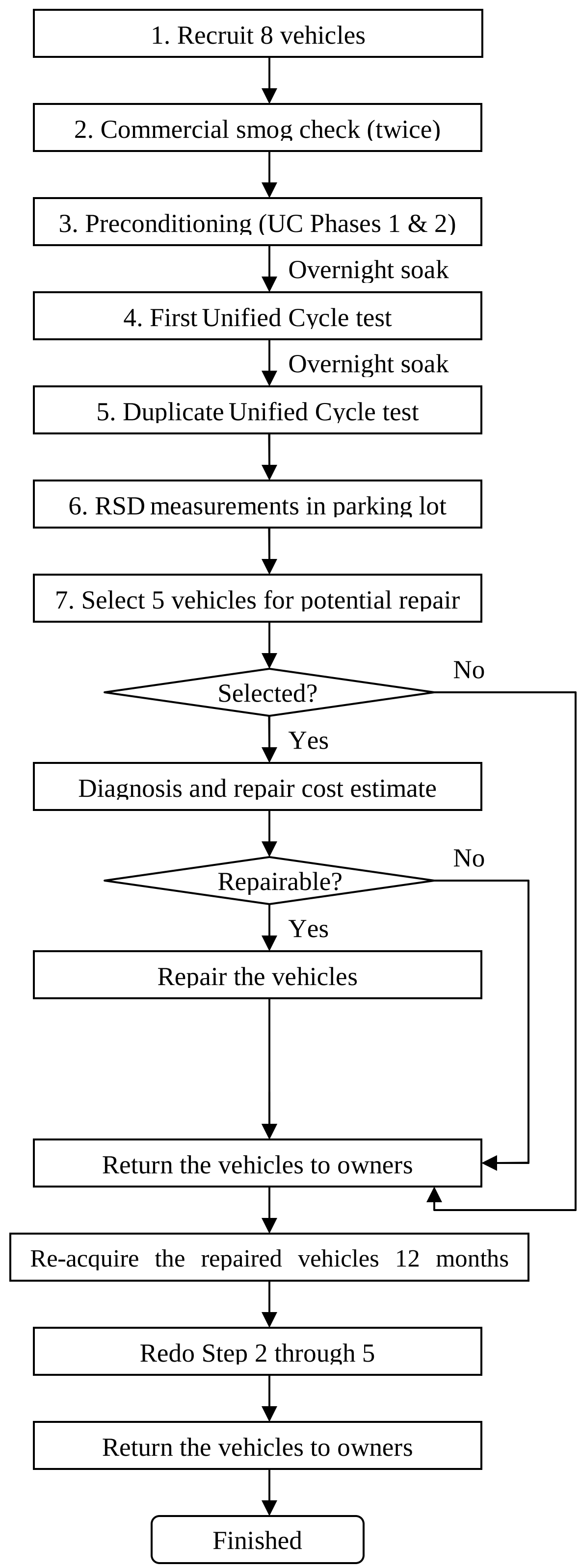


Figure 1. Flow Chart of the Measurement Program

2.3 Emission Measurements

2.3.1 Unified Cycle Testing

All the eight vehicles were tested over the UC cycle to obtain mass emission rates for total PM, THC, NMHC, CO, and NO_X. UC is a more aggressive cycle and more adequately covers typical driving patterns than the Federal Test Procedure (FTP). It is approximately 10 miles in length, with an average speed of 24.8 miles per hour, a top speed of 67 miles per hour, 16.4 percent idle and 1.52 stops per mile. Vehicles tested over UC were found to emit significantly higher compared to vehicles tested over the FTP [21].

All the tests were conducted in CE-CERT's Vehicle Emission Research Laboratory (VERL) equipped with a Burke E. Porter 48-inch single-roll electric dynamometer and Pierburg constant volume sampling (CVS)/dilution tunnel system. A CVS flow rate of 350 standard cubic feet per minute (SCFM) was used for the testing. Particulate sampling was conducted with VERL's 10-inch diameter dilution tunnel. The tunnel was fitted with three PM sampling probes located approximately 10 tunnel diameter downstream of the exhaust mixing flange. The sampling configuration, filter media, and analyses are presented in Figure 2 and summarized below.

- Probe 1 was fitted with 47 mm, 2.0 µm pore size polytetrafluoroethylene (PTFE) membrane filters to obtain total mass particulate emission rates for each phase of the FTP. Each filter assembly was fitted with a primary and a backup filter.

- Probe 2 was fitted with three 47 mm quartz fiber filters for each phase of the UC cycle, respectively. A fourth quartz filter and a PUF/XAD/PUF (PXP) cartridge downstream were also fitted to probe 2 to cumulatively collect particulate samples over the entire UC cycle. The quartz filters as well as the PXP cartridge are stored for possible future analysis for organic and elemental carbon (OC/EC, off Quartz filters), and polycyclic aromatic hydrocarbons (PAHs, off quartz filters and PXP) and n-Alkanes (off quartz filters and PXP).

- Probe 3 was fitted with a TSI DustTrak™ 8520 aerosol monitor for real-time particulate mass measurements and a TSI 3022A condensation particle counter (CPC) to obtain real-time particle number. The particle number was initially observed to be over the range of the CPC (10^7 particles/cm^3), therefore a dilutor was placed in front of the CPC (and behind the first port) to provide secondary dilution for CPC measurement starting with the 7th test. The dilution ratio used during the subsequent tests was approximate 12.6:1.

The flow rates for both the PTFE and quartz filter samplings were set to 30 liter per minute (LPM) for most tests. During the first test of vehicle #6 (1963 Avanti), the PTFE filters collected from phase 2 were found to be clogged. The flow rate of PTFE filter sampling for the second test of this vehicle was reduced to 15 LPM.

One DNPH (2,4-dinitrophenylhydrazine) cartridge and one Carbotrap 300 Multi-Bed Thermal Desorption tube (filled with graphitized carbon black adsorbent resin) were also collected for each test to obtain the formaldehyde/other carbonyls and C_4-C_{12} gases, respectively. Since this study did not have sufficient funds to characterize the composition or toxicity of the gas-phase and particle-phase emissions, the collected samples (except PTFE filters) will be stored for possible analysis in future efforts.

2.3.2 Idle and ASM (Smog Check) Testing

A high PM emitter tailpipe screening device (TSD) was developed in this program to distinguish high emitters versus normal emitters. This system is shown in Figure 3 and is described below.

The TSD operates by drawing the entire exhaust flow from the vehicles tailpipe along with excess ambient air into a plenum which narrows to pipe about 4 inches in diameter. The combined exhaust plus ambient air travels at least 10 diameters downstream, past a sample probe, and through a medium pressure blower with a flow rate of 150 cubic feet per minute (CFM). A sample of approximately 2 liters per minute is withdrawn through the sample probe into a TSI DustTrak™ particle mass monitor. Because the blower flow rate is roughly constant, the system roughly constitutes a Constant Volume Sampler (CVS) in miniature, which we call a mini-CVS. Particle mass concentration (mg/m^3) measured by the DustTrak was multiplied by the main pipe flow rate (m^3/min) to generate a mass emission rate (mg/min). From the Smog Check, the mass emission rate per unit time (mg/min) was divided by vehicle speed (miles/min) to obtain a mass emission rate per unit distance (mg/mi).

The test vehicles were initially sent to a commercial Smog Check station located in Riverside, California. The ambient air was measured with the TSD as the background level. Then the vehicles were operated at idle followed by high speed idle for about 1 minute each and measured with the TSD. After that, a standard Smog Check in the training mode was conducted for each vehicle. The TSD measurement was simultaneously conducted along with the gas emission measurement from the smog station over the Acceleration Simulation Mode (ASM) test at 15 mph (ASM 5015) followed by 25 mph (ASM 2525). For most vehicles, a second duplicate test was conducted for each vehicle on a different day.

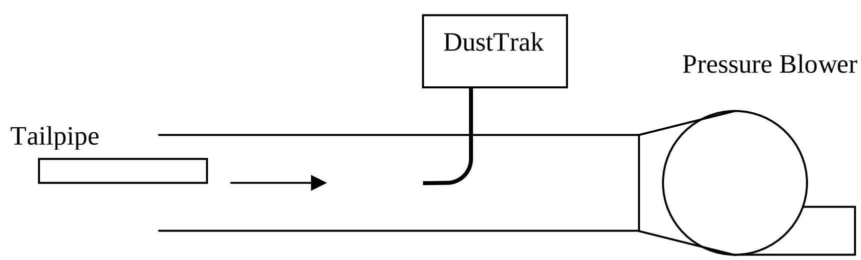


Figure 3. High PM Emitter Tailpipe Screening Device (Not to Scale)

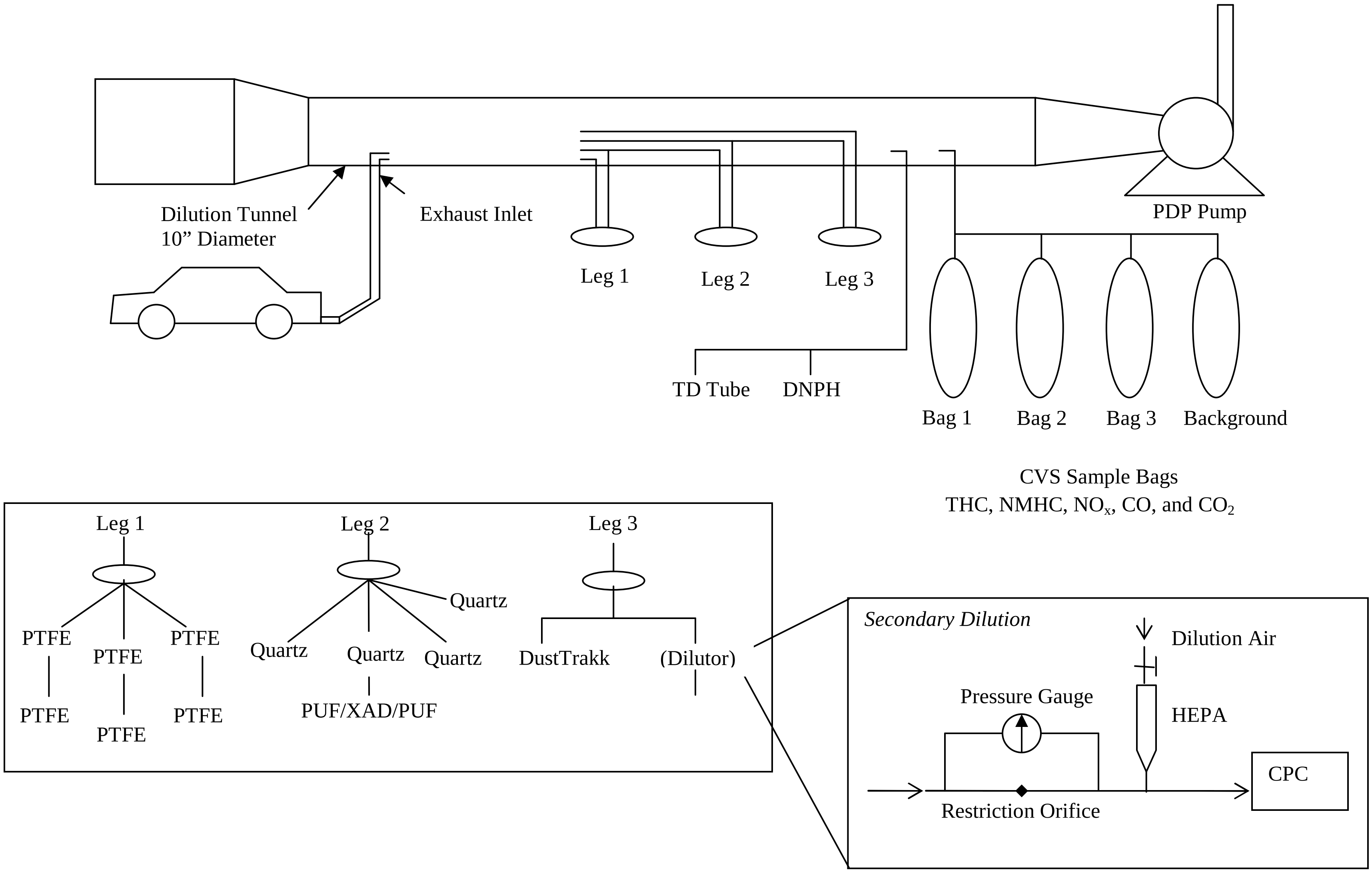


Figure 2. Dilution Sampling System

2.3.3 Remote Sensing

Vehicle emissions remote sensing systems (VERSS) typically measure exhaust emissions from motor vehicles as they are driven past the device set on a street or highway. A video camera system captures an image of the vehicle's license plate while the emissions are being measured. Speed/acceleration sensors also record the speed and acceleration of each vehicle while emissions are being measured [22].

Two remote sensing devices (RSDs), one from ESP and the other from DRI, were chosen to conduct the remote sensing measurements in this program. The ESP system (RSD4000) used in this study includes both PM measurements and gaseous measurement. The PM measurement unit is based on the transmissometer method. Vehicle emissions are measured by casting a narrow infrared (IR) and ultraviolet (UV) beam of light across the road. A transfer mirror module then reflects IR/UV light back to a series of detectors that monitor light intensity at characteristic wavelengths. By measuring the absorption of IR/UV light by the various pollutants in the air, the system is able to calculate the pollutant concentrations in the vehicle exhaust plume [22]. Fuel based emission factors are inferred from the carbon content of the fuel burned (the sum of carbon gases: HC, CO and CO_2) [23]. For gaseous measurements, the IR source is used for CO_2, CO, HC; and the UV source is used for NO [19]. Both the IR and UV sources are used in the ESP system for PM measurement.

The DRI system measures the gaseous emissions using a commercial remote sensing device (RSD3000) that is manufactured by ESP. DRI adds custom built instrumentation to measure PM in conjunction with the gaseous measurements of the RSD3000 unit. The primary PM channel uses UV backscatter light detection and ranging (Lidar) and the secondary channel uses the Lidar as part of a UV transmissometer to measure the cross-road opacity. The two channels simultaneously measure PM backscatter and opacity [23, 24].

These two RSD systems were set up in the CE-CERT parking lot, as shown in Figure 4. These two systems were set as close as possible to each other without interfering with each other. The detection paths were one to two meters apart. All the test vehicles were accelerated past the two RSDs with the vehicles accelerating from various starting distances (25, 50, 75, 100, 150 and 200 feet) and from both directions. At least two measurements were collected for each starting distance in each direction. For most vehicles, a second duplicate test was conducted for each vehicle on a second day. The main purpose of the track testing was to look for relationships between RSD response and the filter mass measurements made using the CVS.

In addition to the track testing, more than 4,000 records of real traffic were also collected using the two RSDs for on-road measurements. The two RSDs were set up at the south side on-ramp of the I-10 Freeway (East) of La Brea Avenue, which is around 6 miles west of downtown Los Angeles (LA). This ramp is the southwest wing of a "butterfly" ramp system with a slight upgrade and a high traffic flow towards downtown LA. On the left-hand side of the ramp, there is an open space shoulder area serving as an Accident Investigation Site (AIS). DRI trailer, ESP van and associated control and analytical systems were parked at the AIS site along with the RSD sensors and cameras. The reflecting mirrors were positioned across the ramp from the AIS. There was an on-ramp stop sign about 75 feet away from the RSDs. Most vehicles were accelerating with an average speed of 17 mph (27 km/h) and an average acceleration of 0.7 m/s^2 while being recorded by the RSD systems. The data collection was conducted between 6:45 AM and 3:50 PM on July 27, 2006 (Wednesday). A total of 4,246 records from 4,225 vehicles were collected (some trucks with relatively long bodies were recorded twice).

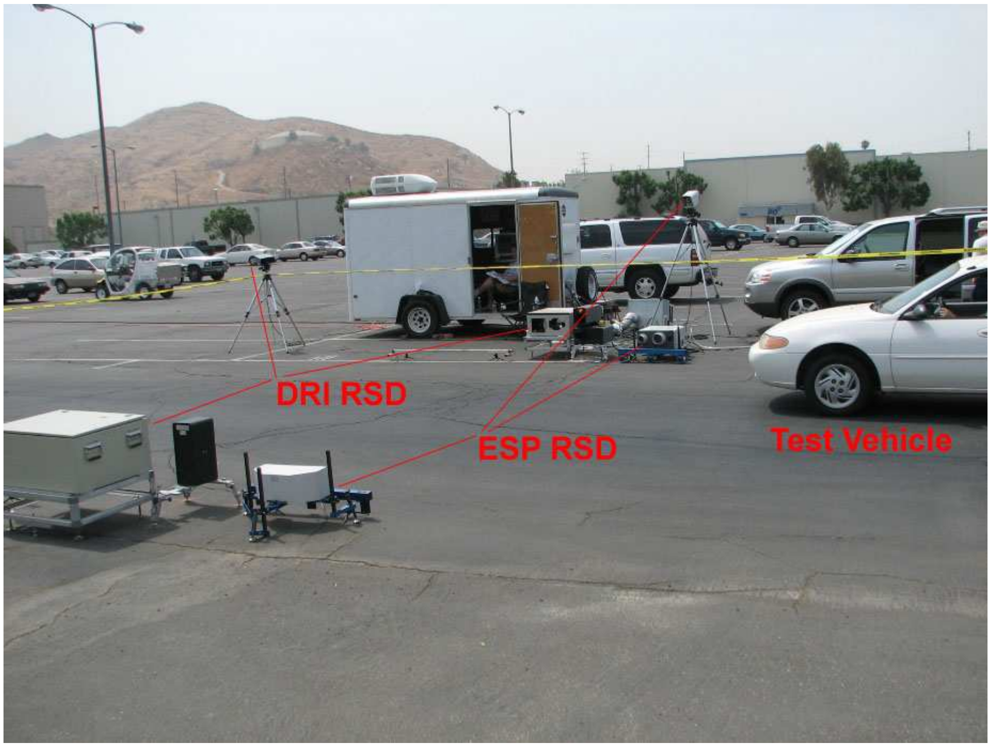


Figure 4. Remote Sensing Measurements in CE-CERT Parking Lot

3.0 Extractive Measurement Results

3.1 Unified Cycle Tests

3.1.1 Gaseous Emissions

Each vehicle was tested twice over the UC cycle. The gas phase emissions for the test vehicles are plotted in Figure 5, and the detailed data can be found in Appendix A. Note the log scale in these plots. The emission rates varied over about three orders of magnitude from vehicle to vehicle. The error bars in the figure represent the high and low values of the two tests for each vehicle. Only a single test is available for vehicle #4 (1981 Toyota Pickup) since the dynamometer lost communication during phase 2 of the second test. For comparison, the Tier 1 FTP standards for each emission component are indicated in the figure with dashed lines. Although the UC cycle is more aggressive than the FTP and generates higher emissions, the FTP benchmark still provides some measure of how "high" the emissions of the high emitters are.

The results show all the visible smokers (#4 through #8) have HC and CO emissions that are relatively high compared to the FTP Tier 1 standard. Some of these emissions were even over the range of the gas analyzers, but were still reasonably measured, as summarized in Appendix B. HC emissions for the visible smokers range from 2.5 to 23.5 g/mi. CO emissions for these vehicles range from 39 to 138 g/mi. The emissions of invisible smokers are all higher than the FTP standards, but not to levels that would represent high emitters, especially considering the more aggressive UC. Vehicle #5 (1995 Dodge Dakota) and #7 (1998 Toyota Camry) have relatively low NO_x. This indicates that these vehicles might be operating under a rich-burn condition.

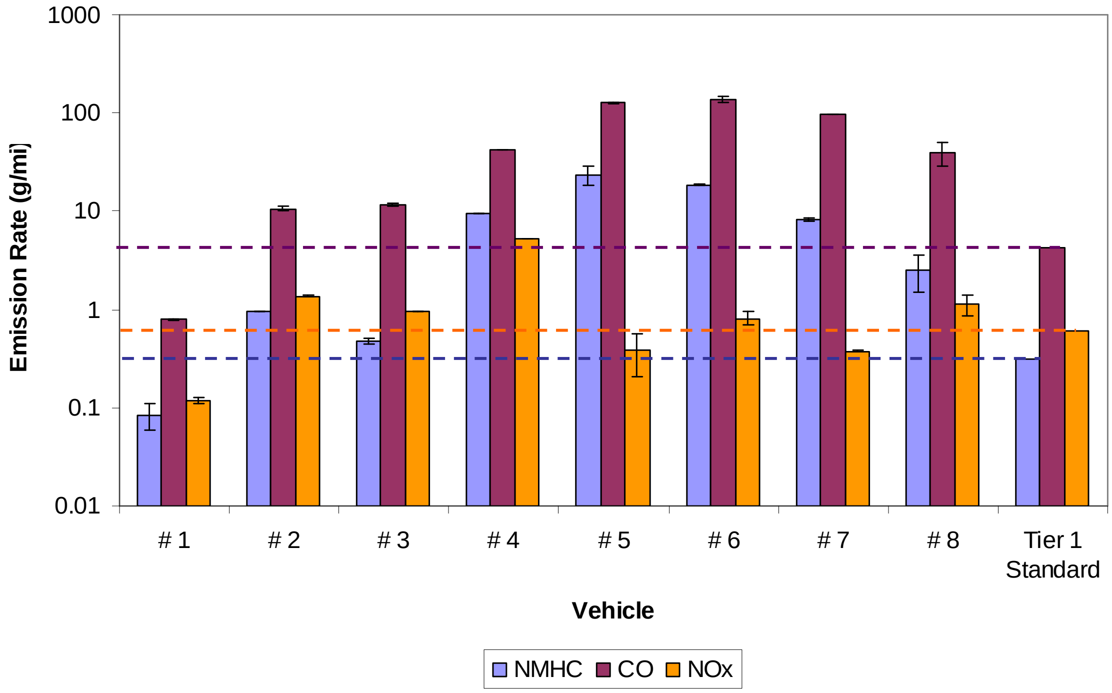


Figure 5. Gaseous Emissions of Test Vehicles over UC

3.1.2 PM Emissions

The PM mass emission rates over the UC cycle for the test vehicles are presented in Figure 6, again on a log scale. Only one test is reported in the figure for vehicle #4 (1981 Toyota Pickup). The error bars in the figure represent the high and low values of the two tests for each vehicle. The results for individual tests are also summarized in Appendix C. The PM emission rates of the visible smoking vehicles (#4 through #8) range from 60 to 1718 mg/mi and are in the range of values found in earlier studies [7, 8, 9, 10, 11]. Vehicles #1 (1997 Ford Escort) and #3 (1991 GMC Sonoma) have emission rates below the current standard (10 mg/mi, based on FTP75) and can be treated as "normal PM emitters". The older invisible smoker (#2, 1985 Toyota Camry) has a PM emission rate of 25 mg/mi, which is about 4 times higher than that of the newer invisible smoker (#3, 1991 GMC Sonoma).

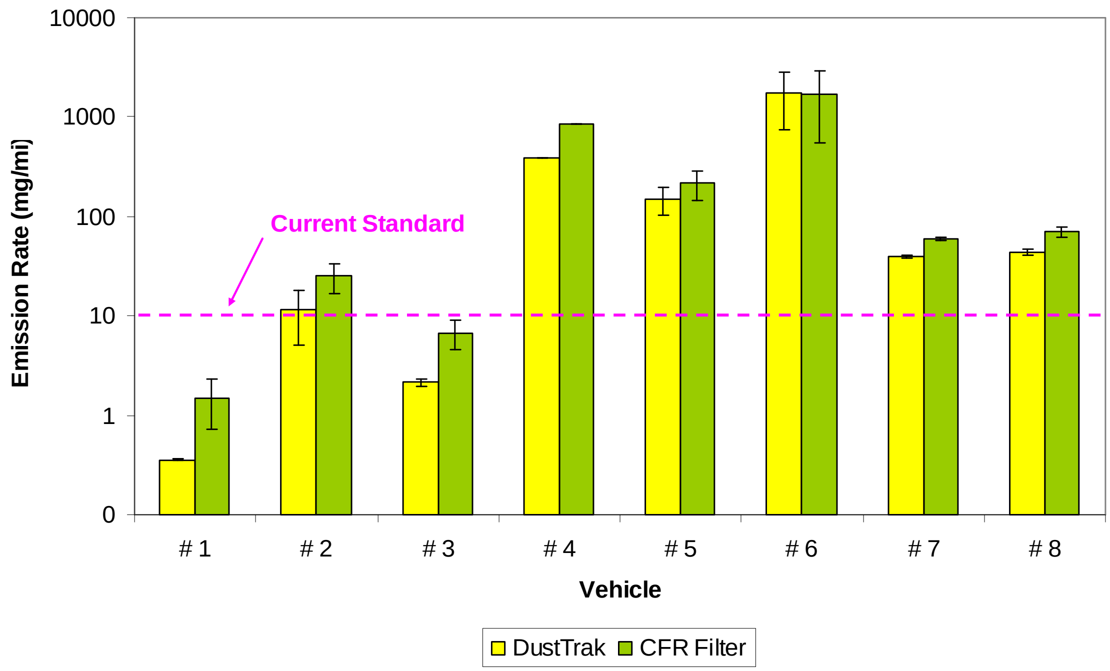


Figure 6. PM Mass Emission Rates over UC

In Figure 6, PM emission rates from both the filter and the DustTrak measurements are presented. The DustTrak gave second-by-second PM mass concentration (mg/m^3). The second-by-second concentration was multiplied by the CVS flow rate (m^3/sec) then integrated over each phase of the test to generate a mass emission rate (mg/phase). The emission rate over the entire cycle was calculated using the same weighting factor as FTP.

The DustTrak is a simple optical measurement that can be correlated with mass given a particular particle composition and size distribution. It is calibrated for National Institute of Standards and Technology (NIST) standard Arizona Road Dust. During this study, the filter based results were in general higher than the DustTrak results except for vehicle #6. During the tests of vehicles #4 and #6, a lot of engine oil was found on the collected filters as the filters were observed to be yellow and wet, with a strong smell. For vehicle #6, the oil that went through the sampling system clogged the filters then caused the sample flow to be much lower than the desired value, thus the PM emission rates based on the filter data were lower than the DustTrak data and probably underestimated the actual value. For vehicle #4, the sample flow was not affected by the engine oil problem, however, the collected oil on the filters (in liquid phase) was included in the particulate mass during the weighing process, therefore the PM emission rates based on the filter data were much higher than the DustTrak data and probably overestimated the actual value. If these two vehicles are excluded, the DustTrak data showed good correlation with filter data among the other 6 vehicles, as shown in Figure 7. Each data point in the figure represents either the emission rate for each phase of the UC cycle or the composite emission rate weighted over the entire cycle

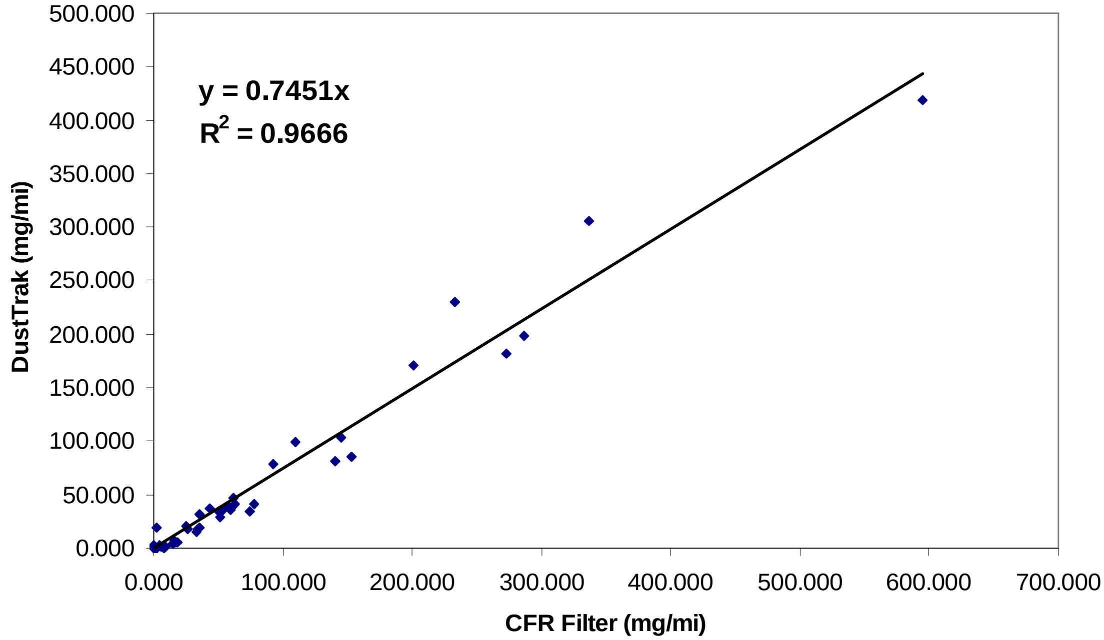


Figure 7. Correlation of DustTrak Data with Filter Data

3.1.3 Particle Number Emissions

Particle numbers were measured by the CPC for each test vehicle over the UC cycle, as shown in Figure 8. The detailed data are listed in Appendix C. In the first few tests, CPC measurements were conducted without secondary dilution and the particle concentrations were observed to be over the limit of the CPC (10^7 particles/cm^3), thus the results listed in Appendix C for these tests are below the actual values. A few readings for vehicle #6 were still over the CPC range even measured with the secondary dilution. Figure 8 includes only tests where the secondary dilution system was used. The smoking vehicles tested here had particle number rates on the order of 10^{13}~10^{14} particles/mi, which is 10~1000 times higher than the FTP particle number emission rates of modern low emitting gasoline vehicles [15]. The vehicle rank for particle number emissions (#6 > #4 > #5 > #7 > #3 > #2 > #1) is basically similar to that sorted by particulate mass emission rates (#6 > #4 > #5 > #7 > #2 > #3 > #1).

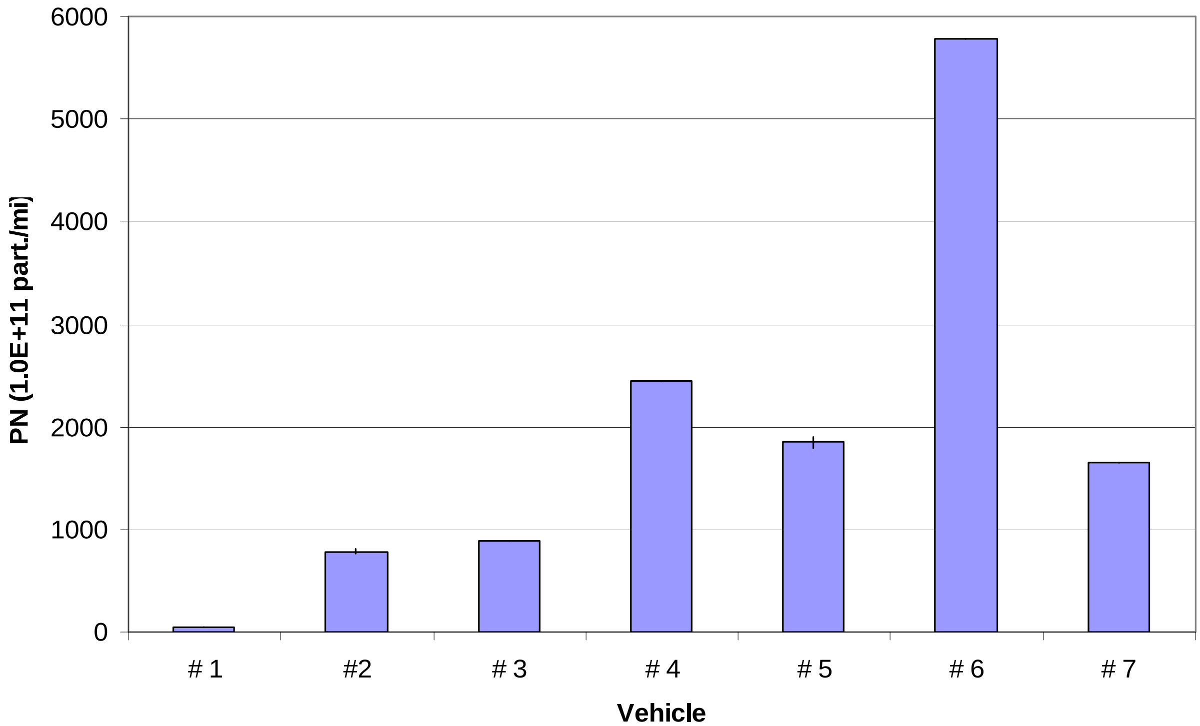


Figure 8. Particle Number Emission Rates for the Test Vehicles
(Vehicle #8 was not included because it was measured without the dilutor and the results exceeded the range of the instrument.)

High numbers of particles were usually generated under hard acceleration events. The real-time mass and number showed similar profiles. As an example, Figures 9 and 10 show the real-time particle number measured by CPC and real-time mass measured by DustTrak, respectively. The large peaks in both figures nearly coincide, although this is not true for all the tests. Sometimes the peaks detected by the DustTrak and the CPC did not always appear in the same positions, because mass depends on not only the particle number but also the size, shape and density. The low emitting gasoline vehicles tested in a previous study [15] also showed a similar real-time particle profile as the vehicles tested in this study.

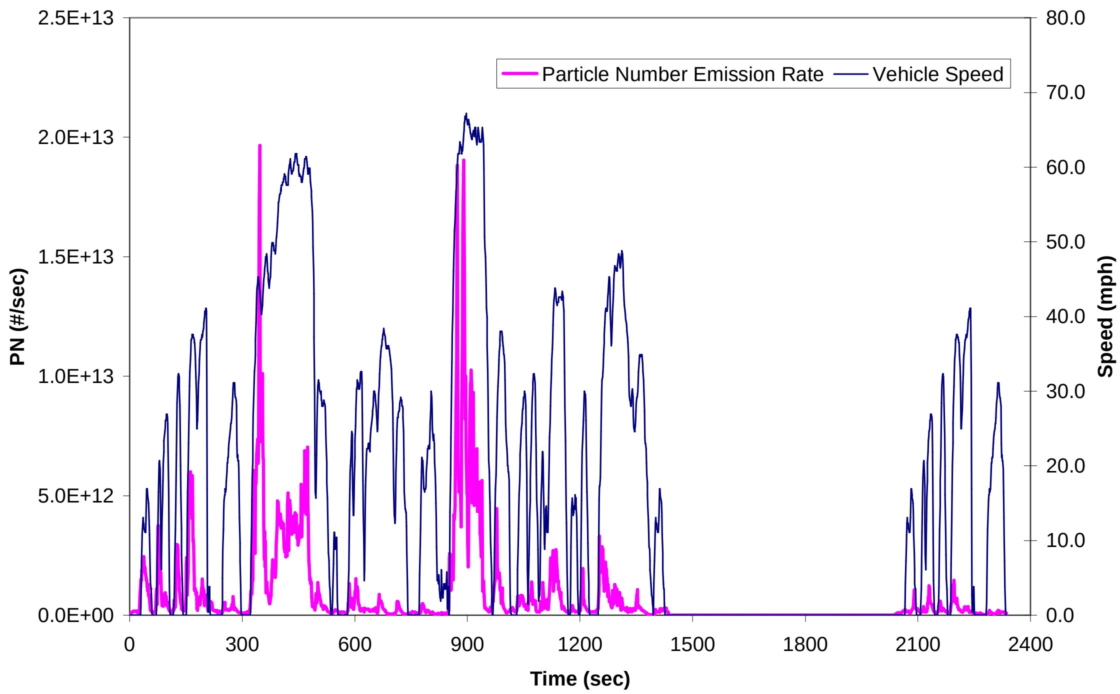


Figure 9. Real-time Particle Number Emission Rate and Vehicle Speed (1995 Dodge Dakota)

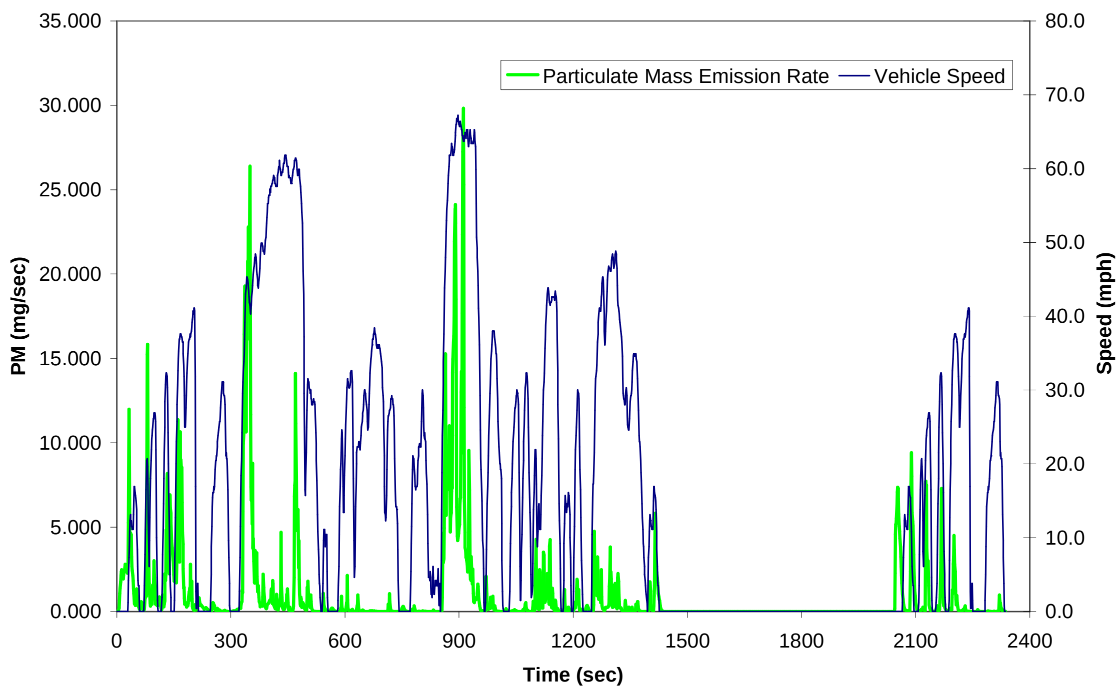


Figure 10. Real-time Particulate Mass Emission Rate and Vehicle Speed (1995 Dodge Dakota)

3.2 Idle and ASM (Smog Check) Tests

3.2.1 Gaseous Emissions from Smog Checks

Each vehicle (except vehicle #5) was tested twice at the same commercial Smog Check station located in Riverside, CA. The Smog Check results are summarized in Table 2 and detailed data can be found in Appendix E. Vehicle #5 (1995 Dodge Dakota) had very high HC emissions, which were over the range of the gas analyzer. Most heavy smoking vehicles failed both of the two smog checks. However, one heavy smoker (vehicle #8, 1986 Mitsubishi Max, grey smoker) passed one of the two smog checks and one moderate smoker (vehicle #2, 1985 Toyota Camry) even passed both smog checks. Two vehicles failed the smog checks, but not as Gross Polluters (GP). The result indicated that adding a PM measurement to the Smog Check program could identify some high PM emitting vehicles that would otherwise pass through the program.

Table 2. Smog Check Results of the Test Vehicles

Vehicle	First Smog Check		Second Smog Check	
	Pass	Failed Emissions	Pass	Failed Emissions
1 (Baseline)	√		√	
2 (Moderate Smoker)	√		√	
3 (Moderate Smoker)	√		×	HC
4 (Blue Smoker, Light)	×	HC, NO	×	NO
5 (Black Smoker, Light)	N/A		N/A	
6 (Blue Smoker, Heavy)	×,GP	HC, CO	×,GP	HC, CO
7 (Black Smoker, Heavy)	×,GP	HC, CO	×,GP	HC, CO
8 (Grey Smoker)	√		×	HC, CO

GP: Gross Polluter. N/A: The test for vehicle 5 was prematurely aborted because the HC emission was over the range of the gas analyzer.

3.2.2 Particulate Measurements from Tailpipe Screening Device

A min-CVS was used as a Tailpipe Screening Device (TSD) to test PM emissions at idle, high speed idle, and over the ASM tests. The ambient air was also measured. The detailed results were summarized in Appendix F. A comparison of PM emission rates over ASM 5015/2525 and UC tests is presented in Figure 12. The “high PM emitters” defined by filter measurements over Unified Cycle testing (vehicles #2, 4, 5, 6, 7, 8) also showed PM emission rates higher than the current standard (10 mg/mi, based on FTP75) for the ASM tests. The test for vehicle #5 was prematurely aborted but part of the test was still measured and reported here. Vehicle #2 was idled for a relatively long time (> 30 minutes) before the Smog Check and a lot of visible white smoke was observed. This might have caused the very high PM emissions measured during the ASM tests.

If we set the filter based PM emission rate of 10 mg/mi as the cut point to distinguish the high emitters and normal emitters and set a cut point for the TSD, the two cut points divide the plotting area into 4 regions, as shown in Figures 13 and 14: Region 1: normal emitters identified by both methods; Region 2: normal emitters identified by laboratory method but misidentified as higher emitters by TSD; Region 3: high emitters identified by both methods; Region 4: higher emitters not identified by TSD. Again these plots us a log scale, so the differentiation between low and high emitters is much larger than might appear at first glance. An appropriate cut point for the TSD in the Smog Check program would be designed to separate the high emitters and normal emitters as efficiently as possible, i.e., to maximize the numbers of vehicles located in region 1 and region 3 while minimize the numbers of vehicles located in region 2 and region 4.

In this study, it was possible to choose cut points, 10 mg/minute and 10 mg/mile, so that all of the vehicles were identified in either region 1 (normal emitters) or region 3 (high emitters). To implement cut points in an actual I/M program would require a much larger test data set collected from vehicles routinely entering Smog Check stations for ASM or idle testing. However, the cut points shown do illustrate the potential of the TSD to assist vehicle inspection and maintenance (I/M) program for both the enforcement applications of clean screening (CS) and/or gross emitter identification (GEI). .

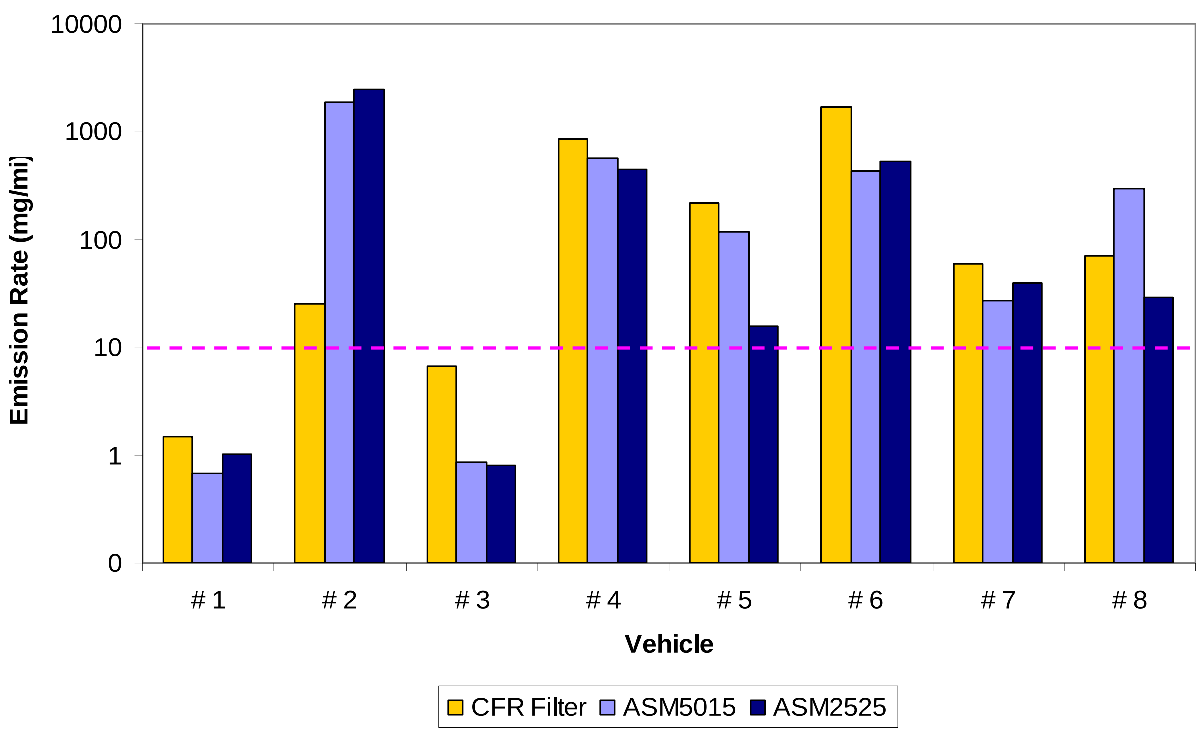


Figure 12. Comparison of PM Emission Rates over ASM 5015/2525 and UC Tests

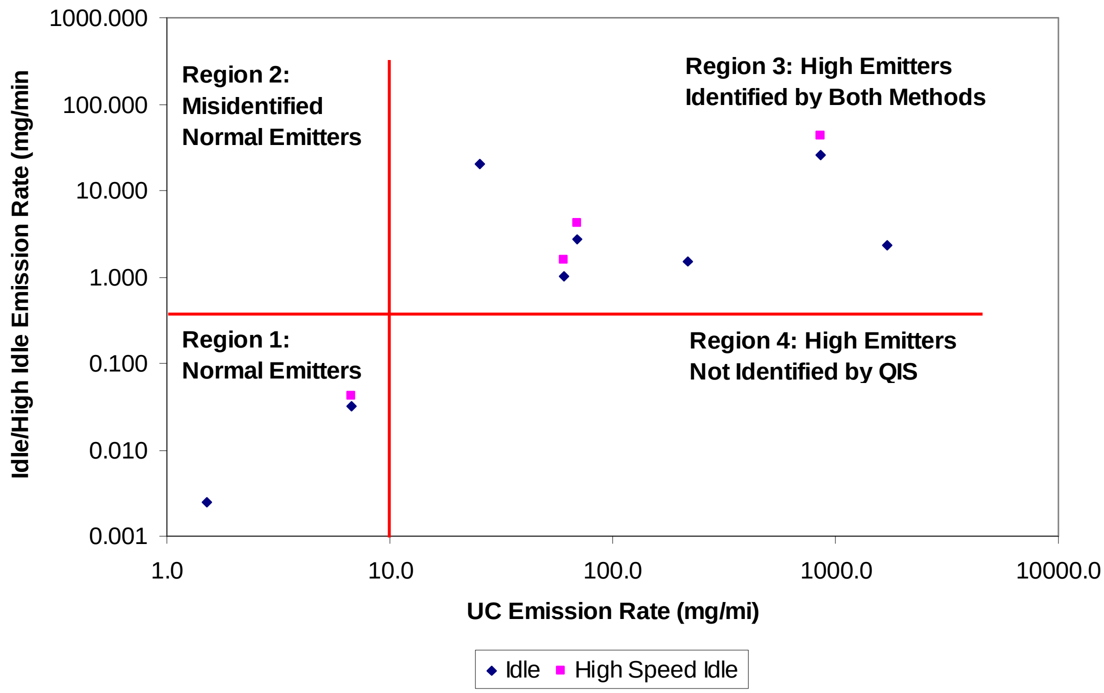


Figure 13. High PM Emitters Identified by TSD over Idle/High Speed Idle Tests

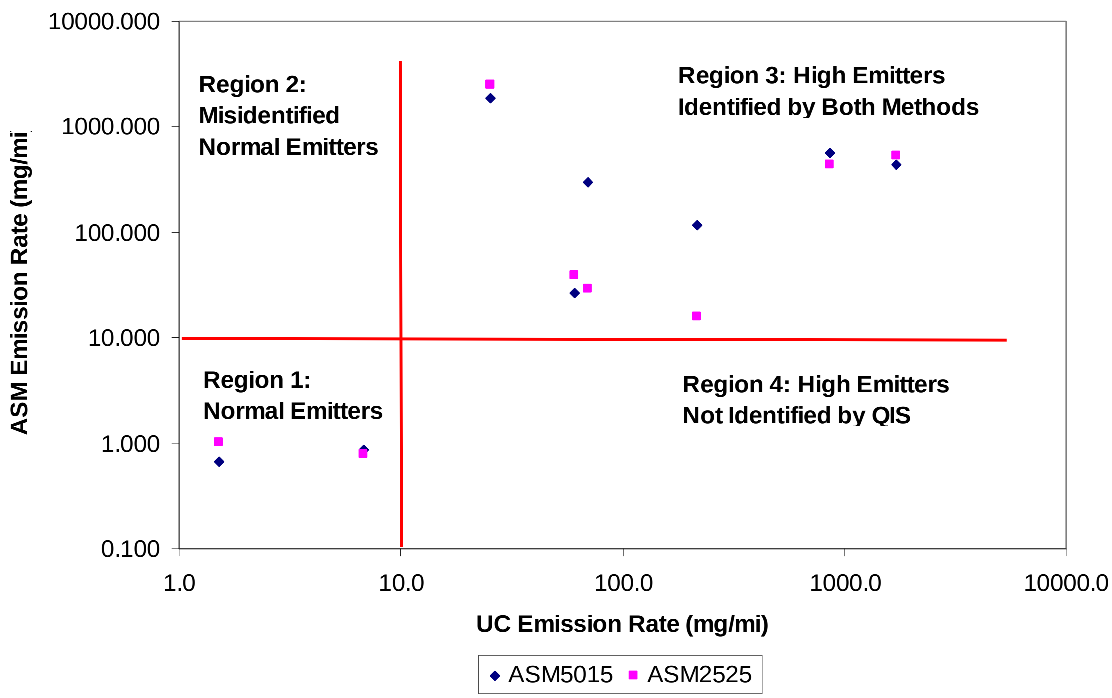


Figure 14. High PM Emitters Identified by TSD over ASM Tests

3.3 Vehicle Diagnosis, Repair, and Retesting

A total of five vehicles were sent to local dealers for diagnosis and repair estimates. The types of problems and the costs are summarized in Table 3. The repair estimates for two of the vehicles were considerably higher than the $2,000 limit. These vehicles were burning excessive amounts of oil or coolant and needed new or rebuilt engines. These repairs were not made.

The types of repairs that were feasible included items such as injectors, EGR, sensors, catalysts etc. The initial estimates to repair vehicles 5, 7 and 8 were each roughly between $500 and $1000. However after initial repairs were completed, further problems were discovered with the vehicle in each case. For example, the 98 Camry was in relatively good condition, having only a bad O_2 sensor. However, the vehicle had been operated so long in a rich, smoking condition that once the O_2 sensor was replaced, it was found that the catalyst had been destroyed. Our final repair costs ranged from $1,700 to $2,200. Experience with this small set of vehicles leads us to suspect that restoration of any "smoking vehicle" at the dealer is likely to cost as much.

Table 3. Diagnosis and Repair Results of the Test Vehicles

Veh.	Diagnosis	Problems / Operations	Estimated Cost	Repaired	Final Cost
1	(Normal Emitter)			×	
2	√	Excessive clearance in cylinders	$7,935.42	×	
3	(Normal Emitter)			×	
4	√	Head gasket leaking or cracked head	$6,288.61	×	
5	√	Injector, Wiring, Fuel pump	$1,890.00	√	$2,206.99
6	(Non-Catalyst Veh.)			×	
7	√	A/F Sensor, EGR valve, Catalyst	$1,900	√	$1,988.23
8	√	Valve guide seals, Carburetor	$1,721.76	√	$1,683.03

The vehicles were repaired shortly after the initial testing. Problems with the laboratory CVS measurement system delayed re-testing to determine the effectiveness of repairs. Vehicles were returned to their owners, and it was approximately one year later that the vehicles were re-acquired and re-tested. At this time we also re-acquired and re-tested the two non-repaired vehicles under a separate program, and those results are also included here.

As measured one year after repair, the repairs were very effective at reducing PM for two vehicles and ineffective for one vehicle. Table 4 shows the results of PM filter mass over the Unified Cycle. PM emissions from vehicles 5 and 7 decreased over 90%, while PM emissions from vehicle 8 increased by 28%. The gas phase data are consistent with those results. Table 5 shows results of the Smog Checks on the repaired vehicles. Vehicles 5 and 7 passed their post-repair emission tests, while vehicle 8 failed to pass for hydrocarbons. The gas phase results for the Unified Cycle are shown in Appendices A1 (original), A2 (repaired), A3 (change). The repairs reduced NMHC emissions by over 90% for vehicles 5 and 7, but only 44% for vehicle 8.

Table 4. Change in PM Emissions of the Repaired and Unrepaired Vehicles

	Vehicle Smoke	Vehicle Name	Vehicle Repair	UC PM Wghtd mg/mi	UC PM Wghtd mg/mi	Mean mg/mi	Diff. % of mean	Change mg/mi	Change % of Orig.
1	Baseline	97 Ford Escort	Original	2.3	0.7	1.5	105%		
			no repair	4.2	1.4	2.8	102%	1.3	86%
2	Inv. Black	85 Toyota Camry	Original	33.8	16.7	25.2	68%		
			no repair	143.5	72.2	107.8	66%	82.6	327%
3	Inv. Blue	91 GMC Sonoma	Original	9.0	4.8	6.9	61%		
			no repair	-	-	-	-	-	-
4	Blue	81 Toyota Truck	Original	863.2	375.8	619.5	79%		
			no repair	574.2	501.6	537.9	13%	-81.6	-13%
5	Black	95 Dodge Dakota	Original	145.2	287.0	216.1	66%		
			Repaired	13.2	23.3	18.2	55%	-197.8	-92%
6	Blue	63 Studebaker Avanti	Original	2883.0	553.4	1718.2	136%		
			no repair	-	-	-	-	-	-
7	Black	98 Toyota Camry	Original	58.4	62.4	60.4	7%		
			Repaired	2.5	similar	2.5	-	-57.8	-96%
8	Grey	86 Mitsubishi Max	Original	77.6	61.6	69.6	23%		
			Repaired	95.3	83.3	89.3	13%	19.7	28%

Table 5. Smog Check Results at Re-Testing

Vehicle	First Smog Check		Second Smog Check	
	Pass	Failed Emissions	Pass	Failed Emissions
1 (Baseline)				
2 (Moderate Smoker)				
3 (Moderate Smoker)				
4 (Blue Smoker, Light)				
5 (Black Smoker, Light)	√		√	
6 (Blue Smoker, Heavy)				
7 (Black Smoker, Heavy)	√		√	
8 (Grey Smoker)	×	HC	×	HC

4.0 Remote Sensing Measurement Results

4.1 Test Track Remote Sensing

4.1.1 Gaseous Emissions

The gaseous emissions measured with the two RSD systems, along with the UC cycle tests, are shown in Figures 15 through 17. The UC cycle emissions are presented in units of g/kg fuel to provide a more direct comparison with the RSD test methods. The RSD data fro each vehicle presented in the figures are the average of two days' measurements with various starting distances. Only one remote sensing measurement was conducted on each day for the 1995 Dodge Dakota before it stopped operating and no valid data from the DRI RSD are available for this vehicle. The left half of each figure shows emission rates for each vehicle for each of the three systems: UC cycle, EPS RSD, DRI RSD. The right half of each figure is a scatter plot of RSD data versus UC cycle data. Note the use of log scales on the left hand plots and linear scales on the right hand plots.

Vehicles which had higher emission rates over the UC tests generally showed higher emissions as detected by the RSDs. The HC emission rates measured by RSDs are all lower than the laboratory measurements. The CO emissions for vehicles 1, 2, and 3 were much lower for the UC cycle than for the RSD. This is probably due to fact that all RSD measurements were made at moderate to hard acceleration while UC cycle data includes cruising and idle data. NOx emissions for the RSD experiments tended to be higher than those for the dynamometer measurements.

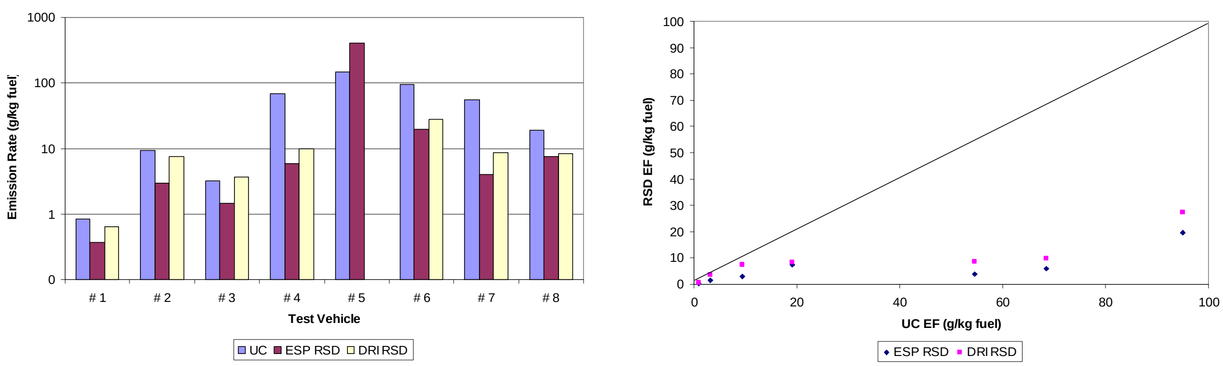


Figure 15. Comparison of RSDs and Laboratory UC Measurements for HC

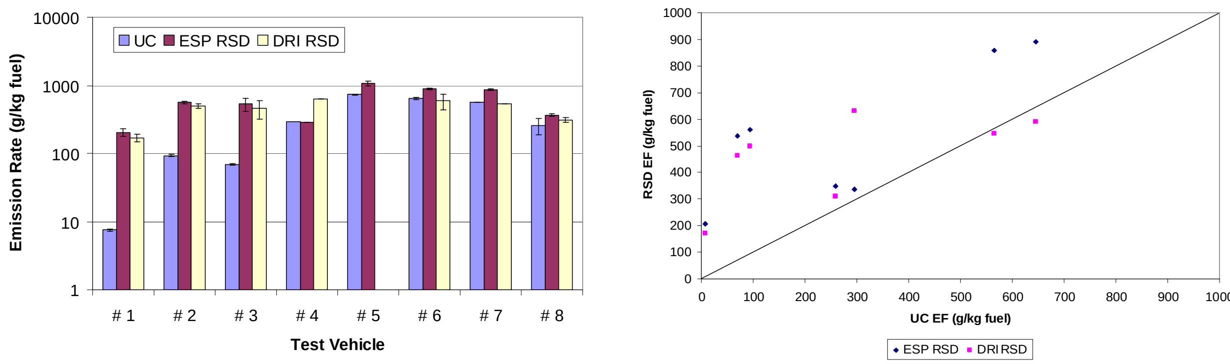


Figure 16. Comparison of RSDs and Laboratory UC Measurements for CO

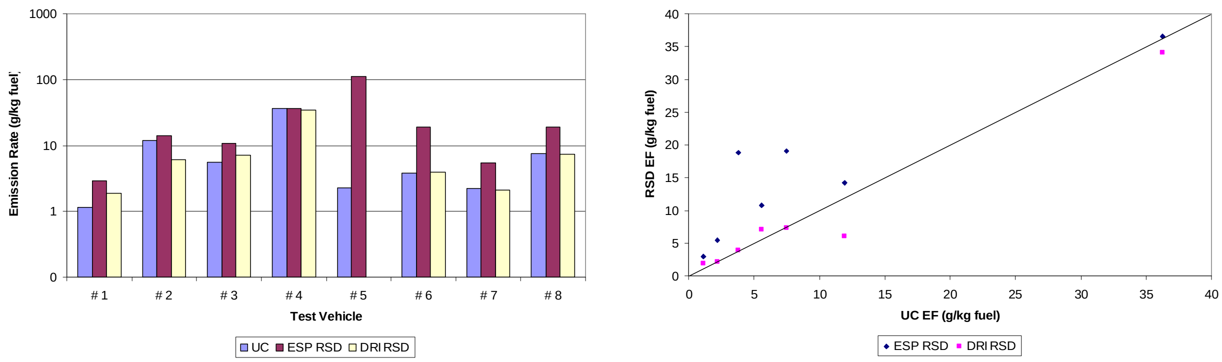


Figure 17. Comparison of RSDs and Laboratory UC Measurements for NO_x

4.1.2 Particulate Emissions

The particulate emissions measured with ESP RSD are expressed as a “Smoke Factor”. It is the theoretical ratio of soot mass to fuel mass at the instant of measurement and is in the unit of grams soot per 100 grams fuel [25]. Both ultraviolet (UV) and infrared (IR) methods were used in the ESP RSD. UV smoke factor is the UV absorbance at 230 nm divided by sum of carbon gases, and mass extinction factor is assumed to be 18×10^4 cm^2/g soot. IR smoke factor is IR absorbance at 3900 nm divided by sum of carbon gases and mass extinction factor is assumed to be 0.59×10^4 cm^2/g soot [26].

Figure 18 shows fuel based PM emission factors in g/kg fuel for the RSD systems and the UC filter measurements. The figure is similar to Figures 15 through 17 for the gases, except that the scatter plot is also on a log scale. The plots show that trends in DRI UV method and the ESP UV method are in general agreement with the trend in UC filter mass, although the trends are so rough that they only appear on a log scale. A weaker but similar trend would also be present for the ESP IR except that the trend is spoiled by the very high filter mass and very low IR response for vehicle 6, the heavy blue smoker. A significant feature of the data shown in Figure 18 is that while trends are similar, there are large systematic differences in the absolute magnitude of the emission factors among methods. These systematic differences, which exceed an order of magnitude, are most likely due to assumptions for particle scattering and absorption efficiencies assumed by the different methods.

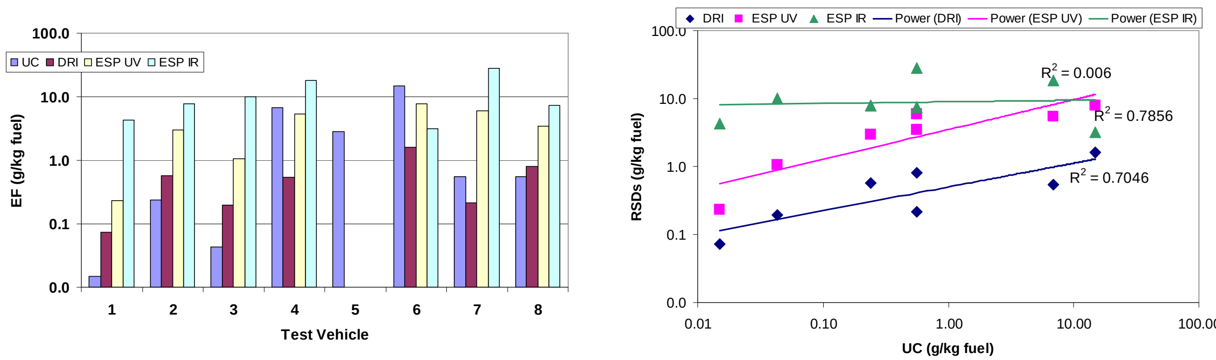


Figure 18. Comparison of RSDs and Laboratory UC Measurements for PM

Another way to look at the RSD PM data is shown in Figures 19 through 21. Each point in these plots represents the average of all results for the vehicle and the starting distance indicated over the two days at the track. These figures show some interesting features.

In Figure 19, the DRI UV response to vehicle 7 is very low. Vehicle 7 is a heavy black smoker, and the result suggests that there is not enough UV light scattered by the heavy black exhaust cloud for the DRI Lidar system to detect it. Vehicle 5, another black smoker, was also not detected by the DRI system on its only pass through the track.

In Figure 21, the ESP IR response to vehicle 7 is very high, but its response to vehicle 6 was very low. Vehicle 6 was easily detected by both the UV systems. Vehicle 6 was a non-catalyst blue smoker known to burn oil. Vehicle 4 is listed as a blue smoker, but its smoke was actually more of a dirty white and probably included particles due to coolant and combustion problems due to the cracked or poorly sealed head. The result suggests that pure unburned oil smoke does not absorb enough IR light for the ESP IR transmissometer to detect it.

Based on the results discussed above it appears that the ESP UV transmissometer system has the best chance of detecting all varieties of smoking vehicle. The ESP IR transmissometer is weak for blue oil smoke, and the DRI UV backscatter is weak for heavy black smoke. These features also spoil the trend relationships for those methods when all vehicle types are included, thereby leaving the ESP UV system with the best correspondence to filter mass trend.

Although it will take additional research to establish the absolute scale of the emission factor, establishing that scale is not essential to use the RSD system in a clean screen (CS) or gross emitter identification (GEI) system. A relative scale would be sufficient.

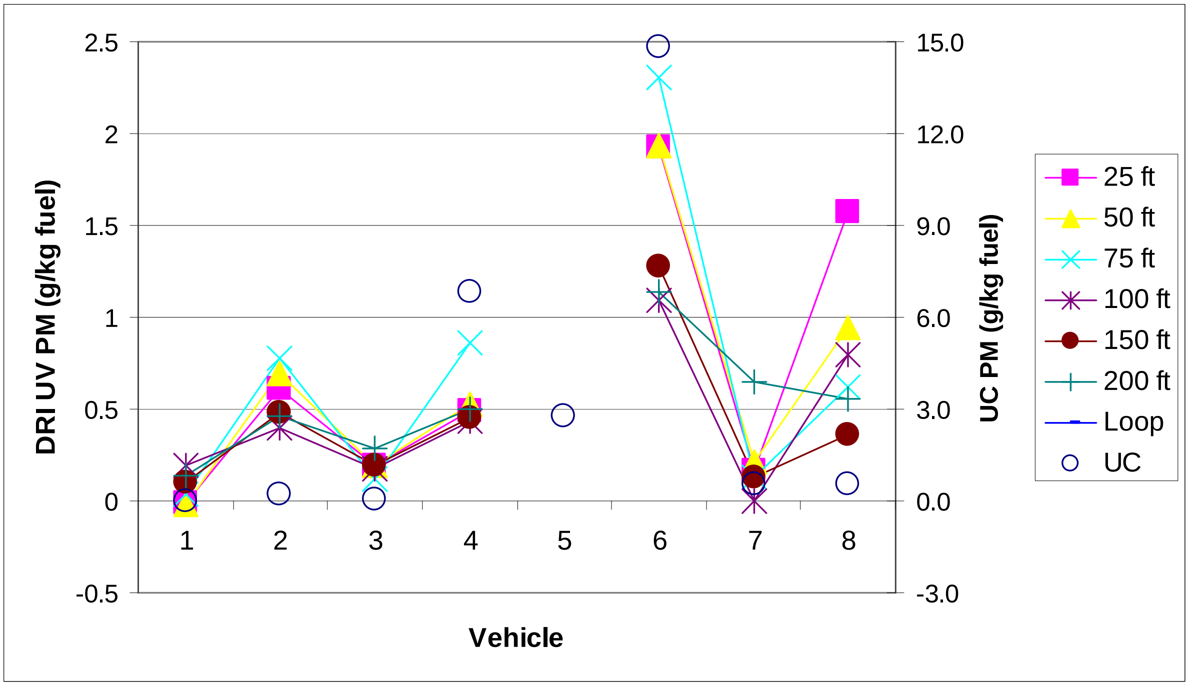


Figure 19. PM Emission Factors Measured with DRI UV Method

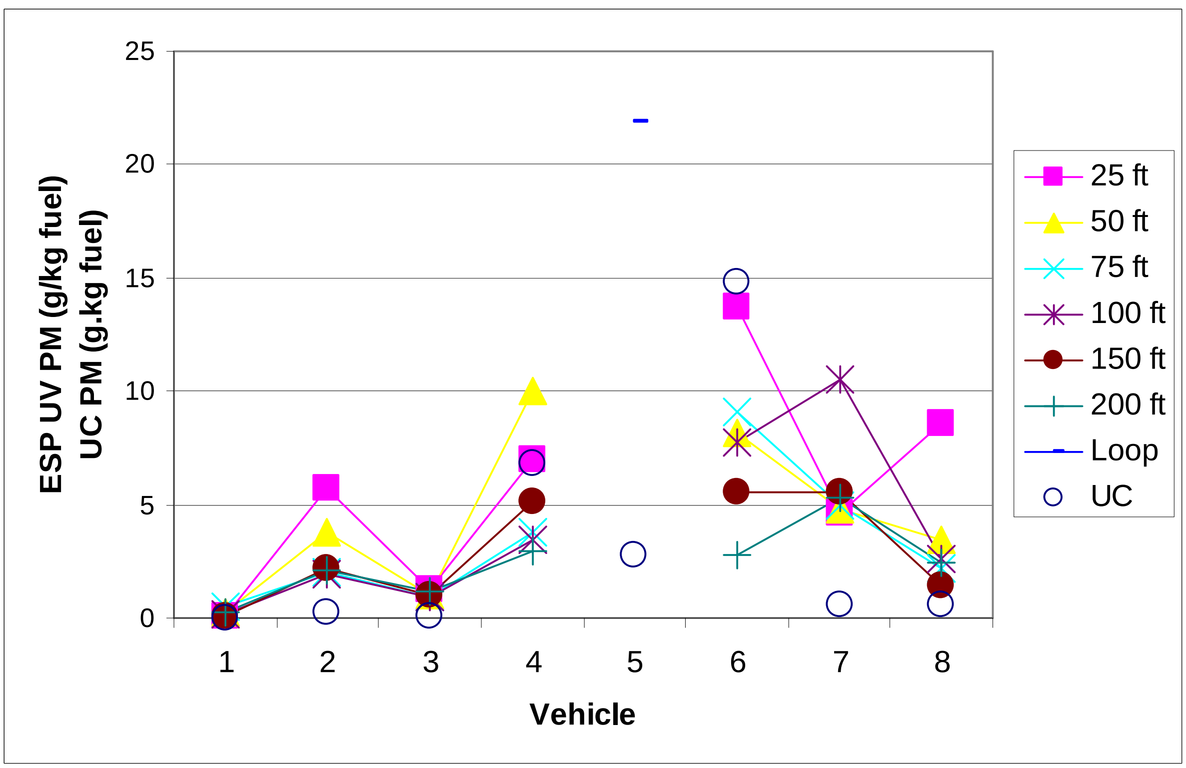


Figure 20. PM Emission Factors Measured with ESP UV Method

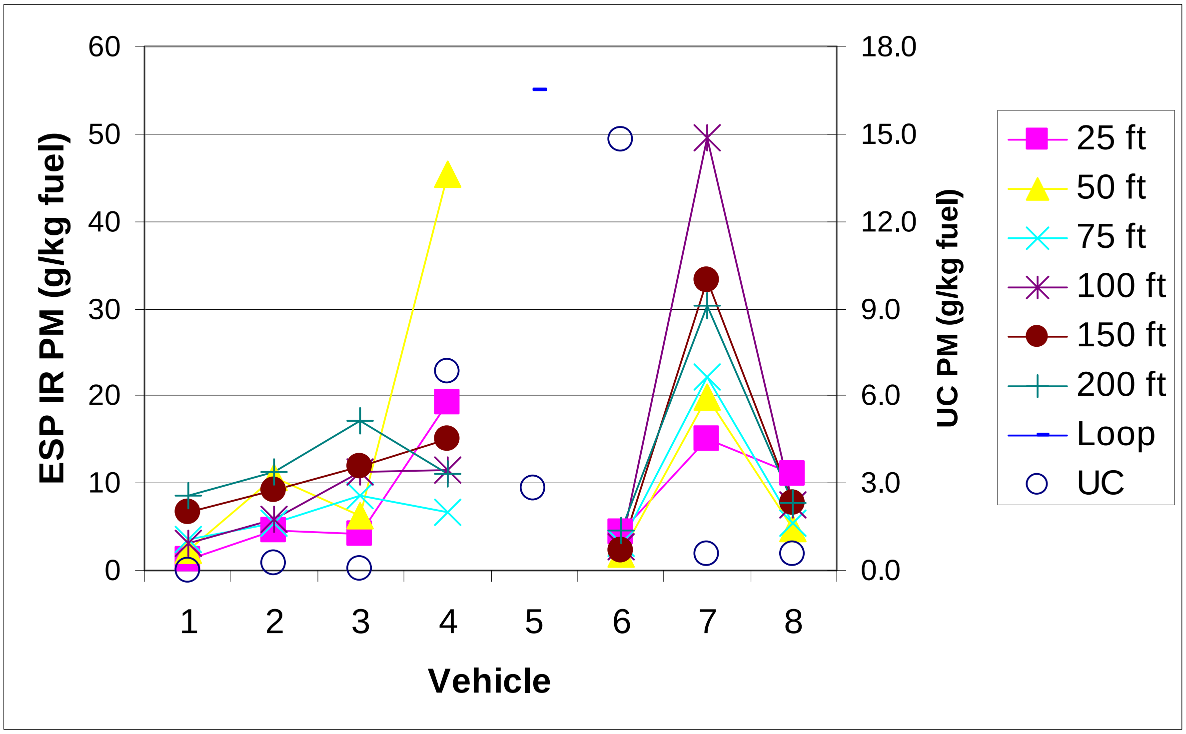


Figure 21. PM Emission Factors Measured with ESP IR Method

4.1.3 Interference from Leading Vehicles

Remote sensing measurements are usually conducted across a single-lane roadway to avoid the interference that would occur from multiple exhaust plumes. However, the plume exhausted from the vehicle in front of the test vehicle may also cause interference to the measurement. In this study, the baseline vehicle (1997 Ford Escort) was driven following two different heavily smoking vehicles to observe the measurement interference of the dirty vehicle to the clean vehicle. Two sets of measurements were conducted: 1997 Escort following 1963 Avanti (vehicle #6, blue smoker) and 1997 Escort following 1998 Camry (vehicle #7, black smoker).

The ESP RSD measurement results of the Escort showed strong interference from the leading vehicle, as shown in Figures 22 and 23. The reported results for the target vehicle were the measurements of the plume when it was passing the RSD minus the background subtraction measured prior to the passage of the target vehicle. The leading vehicle caused positive errors as its exhaust was added to that of the target vehicle and negative errors as its exhaust was added to the background. The errors caused by the leading vehicle to both the target plume and background resulted in larger uncertainty to the desired value. To prevent the increased noise due to interference from affecting real world data, it will be necessary to develop validation criteria for vehicle separation in time and space.

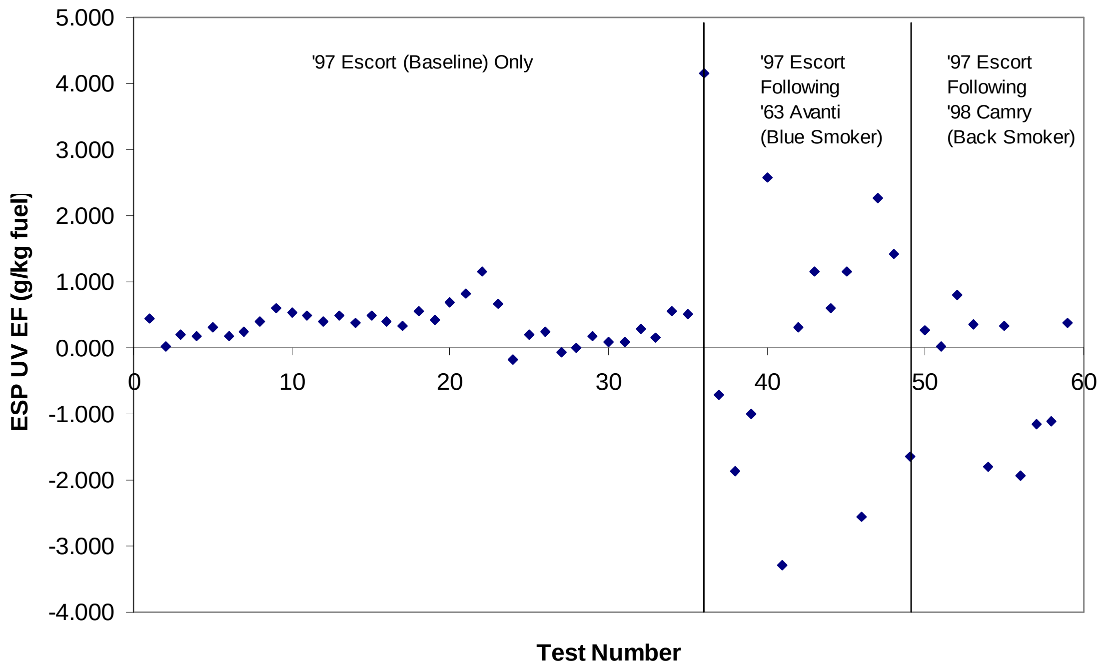


Figure 22. Interference of UV Smoke Measurements from Leading Vehicles

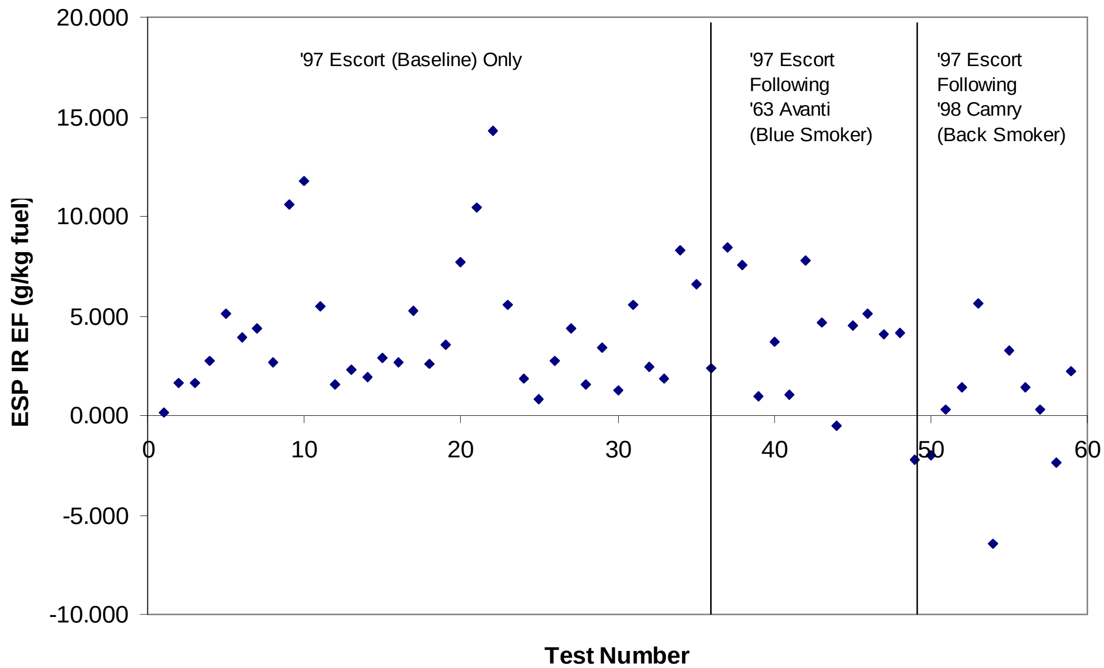


Figure 23. Interference of IR Smoke Measurements from Leading Vehicles

4.2 On-Road Remote Sensing

4.2.1. Vehicle Fleet Distribution

The vehicle fleet distribution was identified by reviewing the 4,246 pictures captured by the cameras. The percentages of each type of vehicle were found to be 52.7% for passenger cars, 19.5% for SUVs, 9.6% for pick-up trucks, and 9.0% for Vans (most of them are mini-vans). These four types of vehicles (3,886 out of 4,225) account for 91% of the fleet and are treated as light duty gasoline vehicles (LDGVs) during the following analysis. A total of 2,835 out of 3,886 LDGVs with valid measurement status were recorded by both RSD systems. The analyses for the LDGVs in the following sections are based on these valid records. Other types of vehicles include medium-size truck (semi-trucks, 7.4%), full-size trucks (trucks, 1.3%), buses (0.2%) and motorcycles (0.3%), as shown in Figure 24.

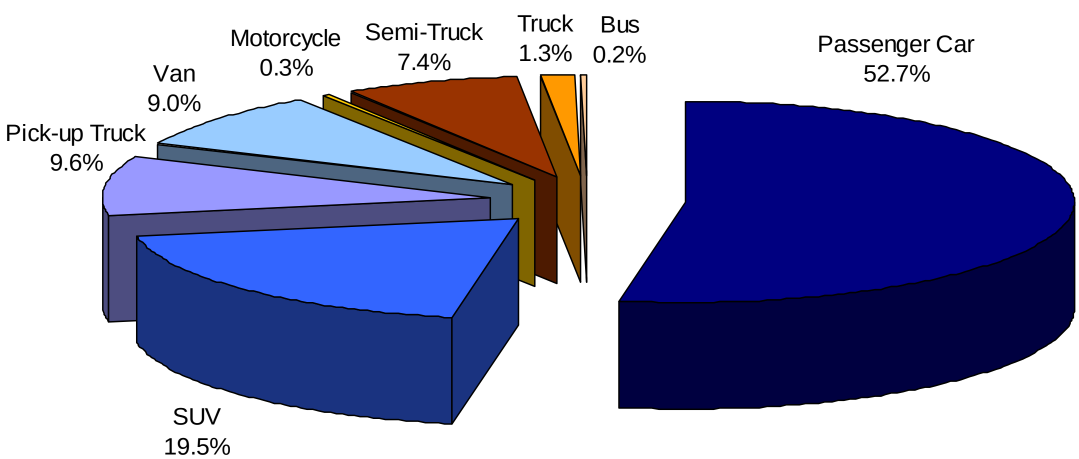


Figure 24. Distribution of On-Road Vehicle Fleet
La Brea Avenue On-Ramp, Los Angeles, July 27, 2006

4.2.2 Gaseous Emissions

The fuel-based emissions of gases and PM for each type of vehicle are summarized in Table 6. The gaseous emission factors are generally found to increase with vehicle weight.

Table 6. Summary of On-Road Remote Sensing Test Results (g/kg fuel)

Fleet	Value	DRI System				ESP System				
		CO	HC	NO	PM	CO	HC	NO	PM_{UV}	PM_{IR}
PC[1]	Mean[6]	**48.5**	**25.69**	**10.62**	**-0.002**	**24.9**	**0.37**	**2.10**	**0.293**	**0.353**
	Stdev	621.4	320.21	111.65	0.412	80.8	1.65	4.56	0.477	0.844
	StdErr	13.6	7.02	2.45	0.009	2.0	0.04	0.11	0.012	0.021
	Max	14521	4562.9	1555.7	14.196	1098.7	49.30	46.78	5.714	12.725
	Min	-12.8	-6.37	-2.51	-1.285	-30.6	-0.63	-14.67	-1.129	-3.656
SUV	Mean[6]	**123.2**	**74.92**	**28.23**	**-0.01**	**15.6**	**0.29**	**1.90**	**0.313**	**0.258**
	Stdev	1220.4	555.32	193.90	0.08	56.8	0.83	4.95	0.394	1.038
	StdErr	44.7	20.36	7.11	0.003	2.4	0.03	0.21	0.016	0.043
	Max	14082	4425.2	1508.8	0.816	883.5	8.04	39.70	3.008	4.299
	Min	-9.6	-6.16	-2.95	-0.372	-17.0	-0.50	-2.65	-0.814	-10.678
PT[2]	Mean[6]	**216.9**	**152.98**	**38.63**	**0.012**	**40.2**	**1.14**	**3.45**	**0.432**	**0.422**
	Stdev	1603.3	783.97	224.44	0.264	124.1	3.78	6.91	0.798	1.317
	StdErr	84.3	41.20	11.80	0.014	7.6	0.23	0.42	0.049	0.081
	Max	14213	4466.0	1522.6	2.909	998.4	36.88	40.57	7.172	15.625
	Min	-7.1	-6.13	-2.69	-0.487	-13.2	-0.47	-2.57	-1.019	-3.412
Van	Mean[6]	**128.6**	**105.02**	**49.66**	**0.022**	**18.5**	**0.55**	**3.23**	**0.382**	**0.308**
	Stdev	1233.0	654.24	255.16	0.361	57.6	1.72	6.79	0.449	0.829
	StdErr	64.5	34.24	13.36	0.019	3.3	0.10	0.39	0.026	0.047
	Max	14273.	4485.0	1529.2	4.721	583.6	21.40	53.56	2.938	6.985
	Min	-9.7	-3.60	-2.35	-0.535	-8.9	-0.22	-2.85	-0.615	-2.524
SFT[3]	Mean[6]	**740.0**	**405.56**	**193.48**	**0.46**	**28.0**	**1.05**	**9.23**	**1.288**	**1.138**
	Stdev	1690.6	949.64	394.22	1.422	114.7	3.11	7.83	1.725	4.232
	StdErr	90.5	50.83	21.10	0.076	7.8	0.21	0.53	0.117	0.287
	Max	14745	4633.3	1579.7	13.778	1230.8	29.18	52.17	13.121	41.125
	Min	-26.7	-4.01	-1.80	-3.597	-22.0	-0.58	-1.74	-0.486	-23.719
LD[4]	Mean[6]	**89.5**	**57.07**	**21.53**	**3×10^{-5}**	**23.7**	**0.45**	**2.31**	**0.319**	**0.324**
	Stdev	978.3	482.21	166.14	0.348	79.8	1.86	5.21	0.501	0.952
	StdErr	16.4	8.09	2.79	0.006	1.5	0.03	0.10	0.009	0.018
	Max	14521	4562.9	1555.7	14.196	1098.7	49.30	53.56	7.172	15.625
	Min	-12.8	-6.37	-2.95	-1.146	-30.6	-0.63	-14.67	-1.175	-6.634
All[5]	Mean[6]	**107.1**	**78.45**	**35.43**	**0.027**	**23.8**	**0.49**	**2.78**	**0.372**	**0.369**
	Stdev	1094.3	565.01	213.66	0.407	81.8	2.00	5.72	0.616	1.099
	StdErr	17.7	9.14	3.46	0.007	1.5	0.04	0.10	0.011	0.020
	Max	14745	4633.3	1579.7	14.196	1230.8	49.30	53.56	7.270	17.982
	Min	-26.7	-6.37	-2.95	-1.285	-30.6	-0.63	-14.67	-1.373	-6.634

1: PC: Passenger Car; 2: PT: Pick-up Truck; 3: SFT: Semi to Full size Truck; 4: LD: Overall Light-Duty vehicle fleet: 5: All: Overall vehicle fleet including all vehicle types; 6: Mean: the mean value of subset data, not including data less than -3σ for each RSD PM measurement; PM_{UV}: PM measured by UV method; PM_{IR}: PM measured by IR method. Data for Buses and Motorcycles were not listed because no valid records were collected from the ESP system.

Correlations of the ESP system with the DRI system for gases are shown for each system in Figure 25, excluding negative data. The plots for CO and NO show good correlations between the two RSD systems, but HC emissions measured by DRI RSD are generally lower than the levels measured by ESP RSD. The reason for the difference in HC readings has not been determined.

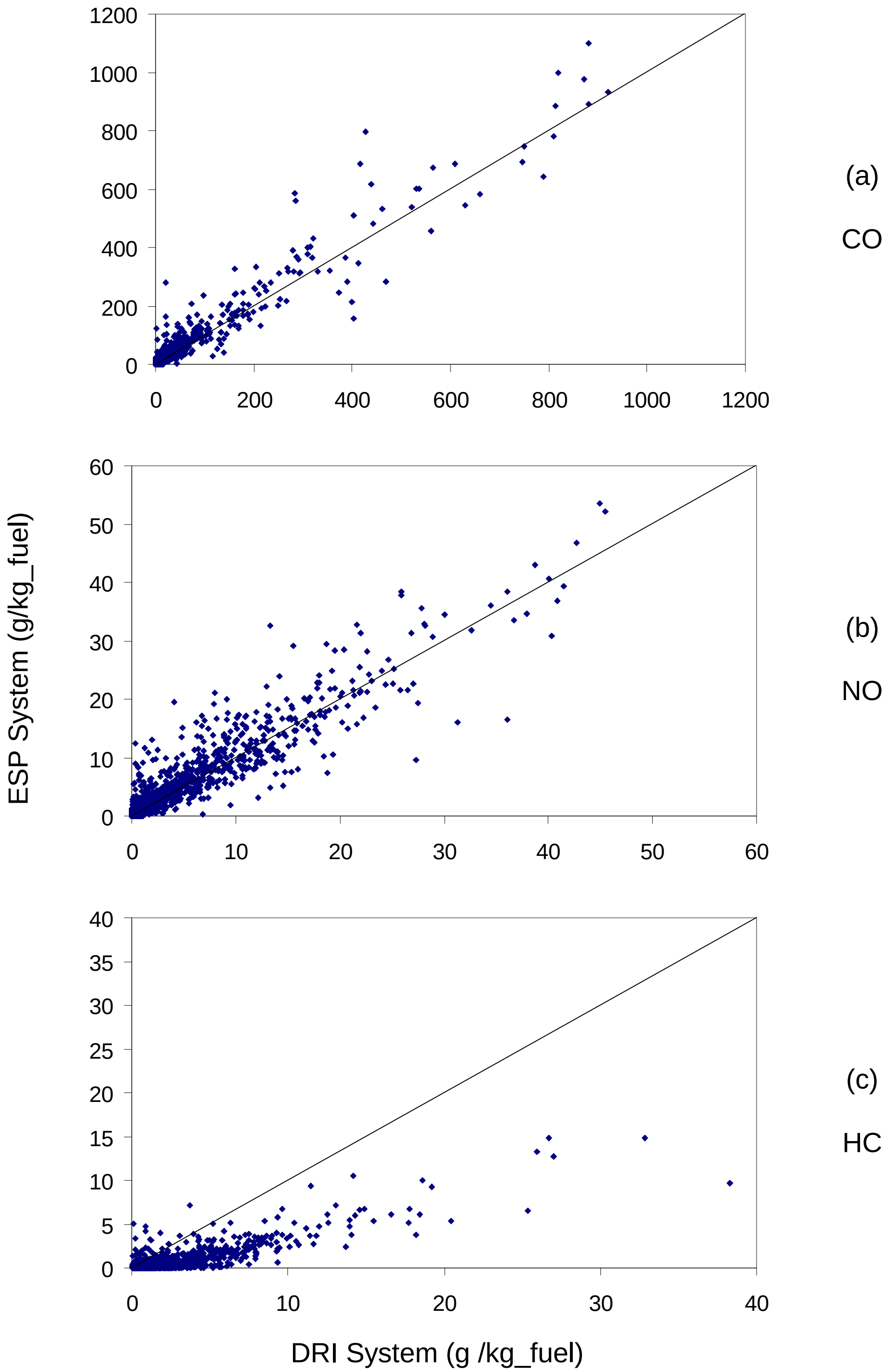


Figure 25. Correlation of ESP with DRI System for On-Road Gaseous Measurements

The good correlation between the two systems shown in the plots for CO and NOx is important because it demonstrates that the data records from the two systems have been properly matched to each other. Neither system captures a valid record for every vehicle, so the initial record sets are not aligned with each other. Each system provides records for a different set of vehicles, although most vehicles are common to both record sets. The record sets were aligned based on the clock time of record capture and the time spacing between vehicles. If the two record sets were misaligned by even one vehicle, then the DRI value and the ESP value would be from different vehicles, and there would be no source of correlation. The correlation shown for CO and NOx demonstrates that the data records were correctly matched to each other. That verification is important to keep in mind when examining the PM results below.

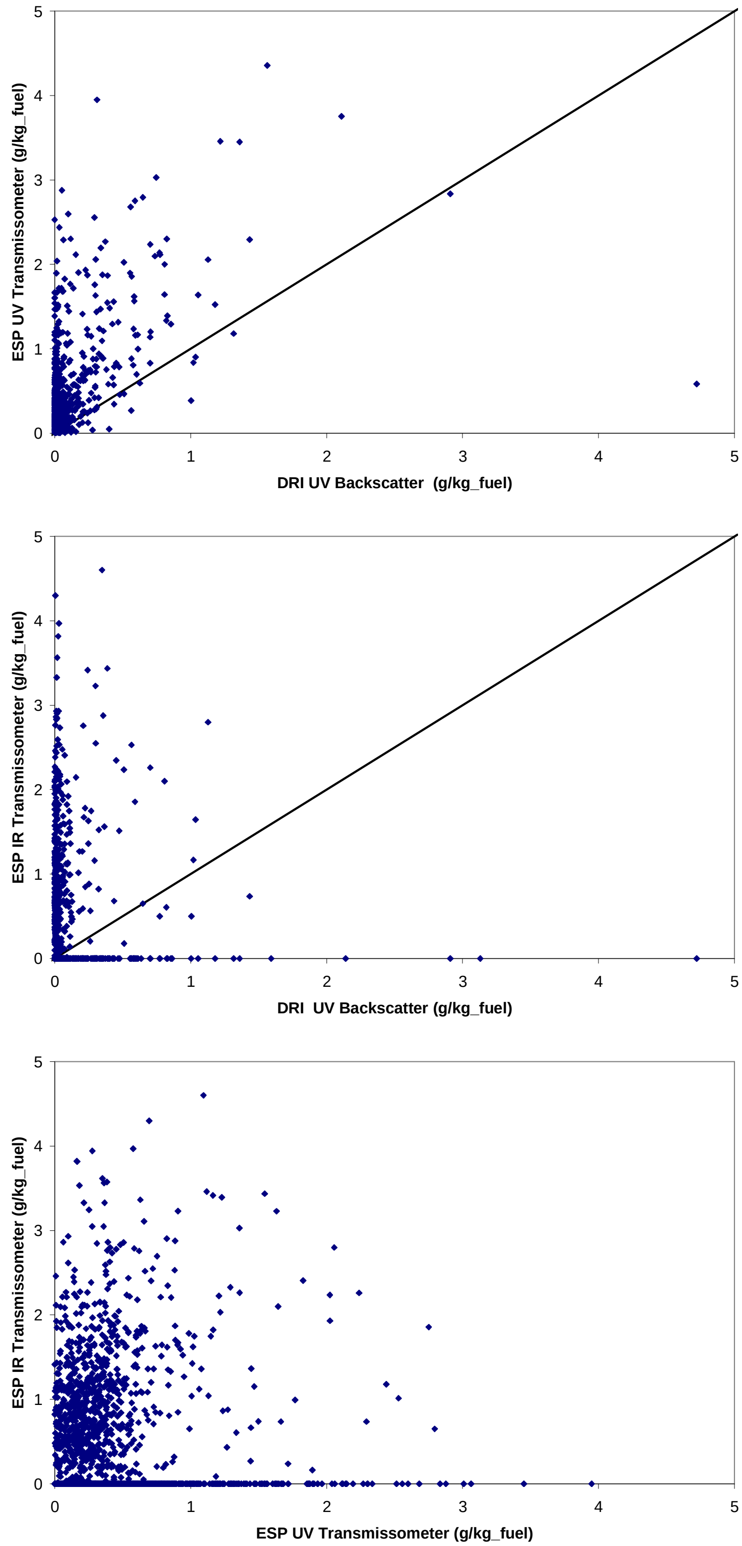
4.2.3. Particulate Emissions

PM Emission Correlations

The fuel-based PM emissions of each type of vehicle are summarized in Table 6. The PM emission factors are also generally found to increase with vehicle weight, similar to the gas phase data. The PM emissions measured by the three RSD methods are systematically different from each other. Measurements by ESP UV and IR transmissometer methods are close to each other while both are much higher than DRI UV backscatter measurements.

PM scatter plots of positive data for the three methods are plotted in Figure 27. It should be noted that a large portion of the test data were found to be negative for the on-road tests, as will be discussed later. The DRI system showed more negative data than the ESP system. Noise, instrumental errors, interference from leading vehicles and other unknown factors may lead to this error. Among these impact factors, the interference from leading vehicles is one of the most likely reasons based on our study from the test track measurements. As these negative data do not represent real PM emissions, they are not included in Figure 27. In contrast to the gaseous emissions, PM emissions measured by the ESP systems and the DRI system show little correlation over the full on-road fleet. The IR system in particular shows almost no correlation with either UV method (R^2=0.10, 0.01, respectively). The UV systems which showed some correlation in the parking lot measurements also showed a poor correlation over the entire on-road fleet (R^2=0.01).

Since some correlation was found for high emitters in the parking lot tests, an additional cross comparison of each method was performed for the highest 2% of PM emitters in the on-road fleet. Since of the each RSD method could identify a different subset of vehicles as being the highest emitting, we defined this subset as any vehicle that was identified in the highest 2% of PM emitters for either the DRI system, the ESP UV system, or the ESP IR system. This subset of vehicles represented 138 vehicles out of 2,835 recorded by both RSD systems. Two percent was selected because previous studies indicated that this is approximately the population of smokers in the general fleet [9, 19]. Among the top two percent high PM emitters identified by any of the RSD systems (a total of 138 vehicles), 23 (17%) were identified by both the DRI UV method and the ESP UV methods, 7 (5%) were identified by both the DRI UV and the ESP IR methods, and 10 (7%) were identified by both



(a)

ESP UV vs. DRI

(b)

ESP IR vs. DRI

(c)

ESP IR vs. UV

Figure 27. Correlation of Three RSD Methods for On-Road PM Measurements

the ESP UV and the ESP IR methods. A total of 6 (4%) vehicles in the top two percent emission levels were detected by all the three RSD methods.

The correlations for the highest 2% of PM emitters (138 vehicles) are shown in Figure 28. In comparing these vehicles, the best correlation is found for the DRI UV and ESP UV methods (R^2=0.37). This is consistent with the greater number of matching vehicles found in the data set. Overall, the correlation has improved in comparison with the entire set of on-road records, but is still relatively poor. The correlation between the ESP UV and ESP IR systems and between the DRI UV ESP IR systems are both poor, even for the subset of high emitting vehicles. Although it may be possible to identify a subset of vehicles for which there is good correlation between the different systems, further investigation in this area is required.

PM Emission Frequency Distributions

Frequency distributions of fuel based PM emissions for the overall LDGV fleet are presented in Figure 29. Note the log scale. Each distribution shows a strong concentration of values near the center of its range, with a very small percentage of outlying extreme values. The mean values are -0.01 g/kg_fuel for DRI UV measurement, 0.32 g/kg_fuel for ESP UV measurement, and 0.24 g/kg_fuel for ESP IR measurement. The PM emission levels of the vehicles tested during the test track measurements are also marked in the Figure. These data points indicate that PM emission levels similar to those of the smoking vehicles tested over the parking lot test track are found in the actual on-road LDGV fleet at the high end of the distribution. The data show that there were many negative values recorded during the on-road measurements. This could be due to issues related to background levels or interferences from leading vehicles, as discussed above. For the DRI system, approximately 66% of the records were identified as negative. For the EPS RSD systems, 16% of the records were identified as negative values for the UV system and 8% were identified as negative values for the IR system.

The fuel based emission factors in g/kg_fuel can be converted to mg/mi by assuming an average fuel economy for each type of vehicle. According to a recent report from EPA, the average fuel economy of the combined car and light truck fleet ranges from 20.7 to 21.1 mpg and has been relatively constant for a decade [27]. A median value of 20.9 mpg was adopted to perform the calculation for this study. The actual fuel economy of the on-road test fleet would likely be lower than the EPA average because most of these on-ramp vehicles were operating under acceleration and their fuel economy may be relatively low. This means that mg/mi estimates based on EPA average fuel economy would represent a lower bound for emissions estimates. Emission rates of 10 mg/mi and 100 mg/mi are converted to the equivalent fuel based emission factors according to the assumption above (average fuel economy is 20.9 mpg) and indicated in each panel of Figure 29. It should be noted that conversion from g/kg fuel to mg/mi is highly depended on the mass extinction coefficients used by either system which can vary depending on the conditions. Nevertheless, this provides some information that can be used in comparing/refining the scattering coefficients.

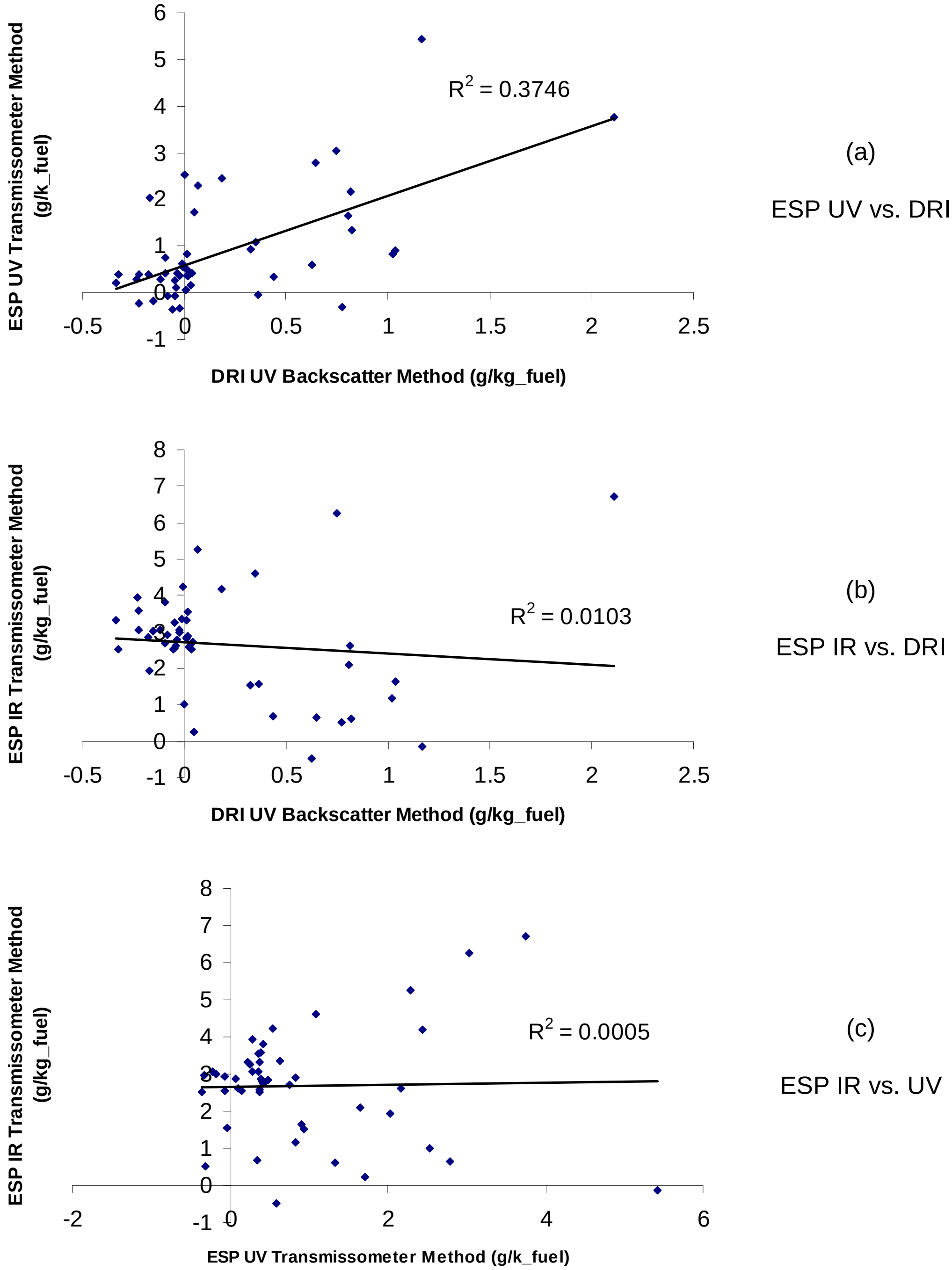


Figure 28. Correlation of RSD Methods for Top 2% High PM Emitters

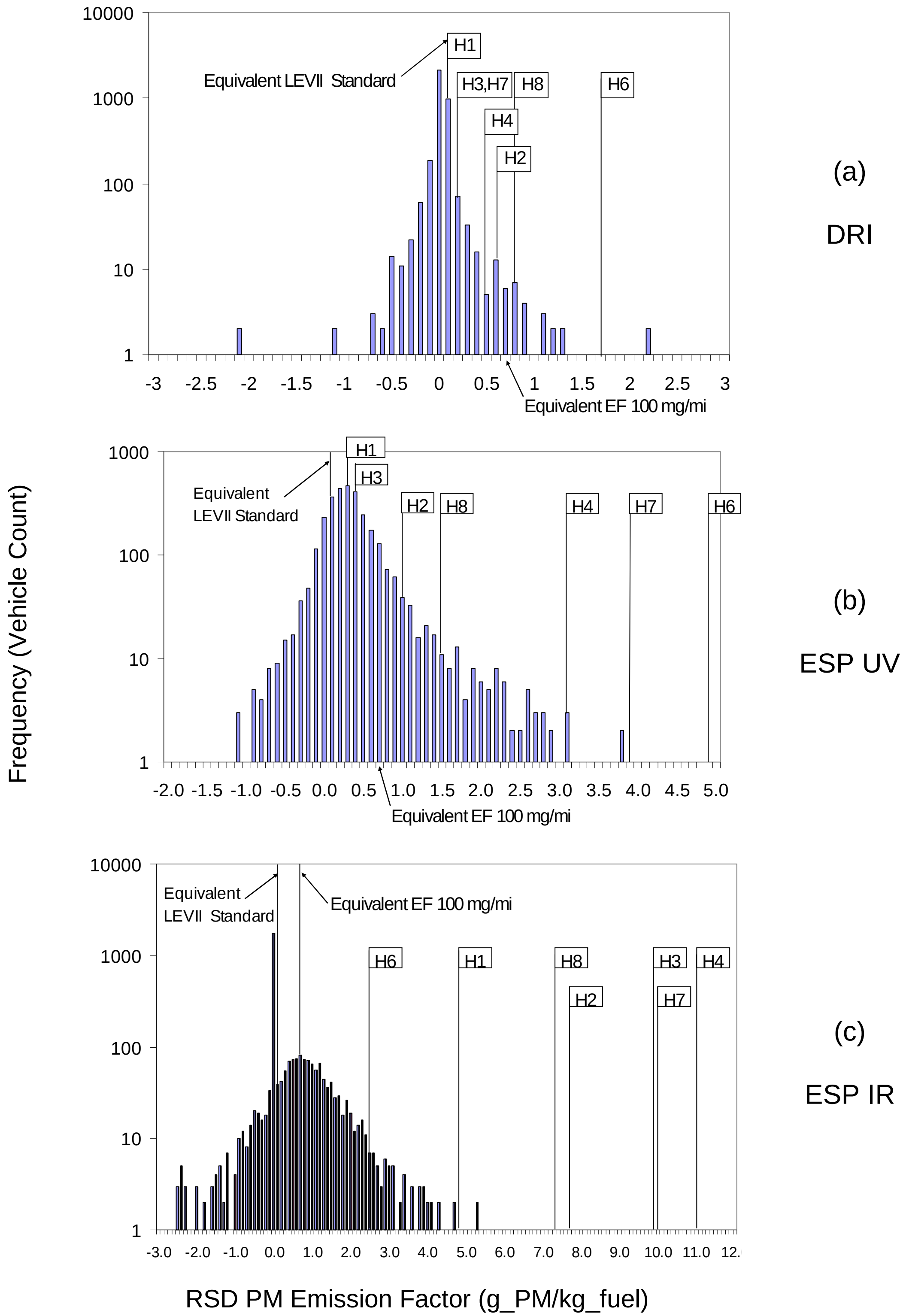


Figure 29. Distribution of On-Road PM Emissions of LDGV Fleet

The number of LDGV vehicles falling into different PM emission ranges is shown in Table 7. Both vehicle count and percentage of each PM range over the entire LDGV are listed in this table. Average PM emission rates for the overall LDGV fleet and the top two percent high emission vehicles as well as are listed in Table 8. Average PM emission rates for the entire LDGV fleet are calculated from the whole set of test records, with the data beyond three standard deviations in the negative side removed. Average PM emission rates of the entire LDGV fleet are 0.027 mg/kg_fuel (0.004 mg/mi), 0.319 g/kg_fuel (43.6 mg/mi) and 0.324 g/kg_fuel (44.3 mg/mi) for the DRI, ESP UV and ESP IR measurements, respectively.

The discrepancy in the scale of results between the DRI and ESP systems has not been resolved. The average PM emission rates of the overall LDGV fleet from this study are compared with results from other RSD studies [28] and several tunnel studies conducted in California [29-34] in Table 59. The comparison indicates that average DRI results are near zero and lower than those measured in tunnel studies. The ESP results are higher than those measured in recent tunnel studies and lower than those of earlier tunnel studies. Average PM emission rates of the top two percent high emitters are 1.0 g/kg_fuel (137 mg/mi), 2.6 g/kg_fuel (358 mg/mi) and 3.9 g/kg_fuel (536 mg/mi) for the DRI, ESP UV and ESP IR measurements, respectively.

Table 7. PM Emission Distribution of On-Road LDGV Fleet

PM Range (mg/mi)	Vehicle Count			Percentage (%)		
	DRI	ESP UV	ESP IR	DRI	ESP UV	ESP IR
<0	1881	453	231	66.35	15.98	8.15
0	49	4	1586	1.73	0.14	55.94
0~5	628	113	12	22.15	3.99	0.42
>5	277	2265	1006	9.78	79.89	35.49
>10	170	2128	994	6.01	75.06	35.06
>50	47	950	861	1.67	33.51	30.37
>100	23	293	609	0.82	10.34	21.48
>500	2	8	19	0.08	0.28	0.67
>1000	1	0	3	0.04	0	0.11

Table 8. PM Emission Rates of On-Road LDGV Fleet

RSD / Fleet	Value	DRI		ESP UV		ESP IR	
	Unit	g/kg fuel	mg/mi	g/kg fuel	mg/mi	g/kg fuel	mg/mi
Overall LDGV fleet	Mean	0.00003	0.004	0.319	43.627	0.324	44.336
	Stdev	0.348	47.568	0.501	68.434	0.952	130.043
	Std error	0.006	0.798	0.009	1.286	0.018	2.446
Top 2% high emitters	Mean	1.004	137.174	2.622	358.273	3.919	535.525
	Stdev	1.477	201.868	1.105	150.934	2.282	311.772
	Std error	0.196	26.738	0.146	19.992	0.300	40.938

Table 9. Comparison of PM Emissions of On-Road LDGV Fleet with Other Studies

Study	Year	Location	Study Method	PM (g/kg)	PM(mg/mi)
This study [a]	2006	Los Angeles	DRI RSD	0.00003±0.006	0.004±0.798
			ESP RSD UV	0.55±0.03	43.6±1.3
			ESP RSD IR	0.57±0.04	44.3±2.4
Mazzoleni et al. [28]	2001	Las Vegas	DRI RSD	0.07±0.013	8.8±1.6
	2002	Las Vegas	DRI RSD	0.047±0.009	5.9±1.1
Geller et al. [29]	2004	Caldecott tunnel	Tunnel	0.07±0.02 [b]	-
Allen et al. [30]	1997	Caldecott tunnel	Tunnel	0.07±0.05 [c]	8.8±0.6
Kirchstetter et al. [31]	1997	Caldecott tunnel	Tunnel	0.11±0.01 [b]	-
Miguel et al. [32]	1996	Caldecott tunnel	Tunnel	0.030±0.002 [d]	-
Gillies et al. [33]	1996	Sepulveda tunnel	Tunnel	0.61±0.31 [b]; 0.80±0.35 [e]	83±43 [b]; 110±48 [e]
Fraser et al. [34]	1993	Van Nuys tunnel	Tunnel	0.66±009	91±11 [f]

a: Values are in the form of mean ± standard error
b: $PM_{2.5}$; c: $PM_{1.9}$; d: black carbon; e: PM_{10}; f: $PM_{1.6}$
Caldecott tunnel is located in San Francisco Bay area, Northern California
Sepulveda tunnel and Van Nuys tunnel are located in Los Angeles area, Southern California

5.0 Summary and Conclusions

In this study, seven smoking vehicles ranging from light smoker to heavy smoker and one baseline vehicle were tested over the UC cycle. Measurements included PM mass as well as particle number. Particulate emissions were also measured with a high PM screening device over idle, high speed idle and ASM tests. Remote sensing measurements were conducted in the CE-CERT parking lot with two systems (DRI and ESP) for all the vehicles. Measurement results from screening device and remote sensing were compared to the Unified Cycle results. The RSD systems were set up at a freeway on-ramp and four thousand data records collected. Key findings of this program are as follows:

- All the visible smokers have HC and CO emissions over the UC cycle that are relatively high compared to the FTP Tier 1 standard. HC emissions for the visible smokers range from 2.5 to 23.5 g/mi. CO emissions for these vehicles range from 39 to 138 g/mi. The emissions of invisible smokers are all higher than the FTP standards, but not to levels that would represent high emitters, especially considering the more aggressive UC. Some smoking vehicles have relatively low NOx emissions probably due to operating under a rich-burn condition.
- The PM emission rates of the visible smoking vehicles range from 60 to 1,718 mg/mi. The older invisible smoker had a PM emission of 25 mg/mi, which is about 4 times higher than that of the newer invisible smoker.
- The smoking vehicles showed particle number rates on the order of 10^{13}~10^{14} particles/mi, which are 10~1000 times higher than the FTP particle number emission rates of modern low emitting gasoline vehicles measured in previous studies.
- . Adding a PM measurement to the Smog Check program could identify some high PM emitting vehicles that would otherwise pass through the program. The Smog Check results for the test vehicles showed that not all the smoking vehicles could be screened by the current Smog Check program
- A mini-CVS screening device can separate the normal PM emitters and the high PM emitters over both the idle/high speed idle and ASM tests.
- Five vehicles were sent to dealers for diagnosis and repair estimate. Two vehicles required repairs in excess of $5,000 and were not repaired. The repair costs for the other three vehicles ranged from $1,700 to $2,200. One year later, the repaired vehicles were retested. The two newer model year vehicles were found to have very low PM emissions, while the oldest model year vehicle still had very high emissions. This small sample suggests that smoke due to air/fuel mixture problems can be corrected by repairs, but that older vehicles might still be smokers due to engine wear problems even after air/fuel mixture problems have been repaired.
- Based on track data, vehicles that had higher emission rates over the UC tests generally showed higher emissions as measured by the RSDs for PM. There is a large discrepancy in scale among the three RSD methods. But relative data should be sufficient to work for clean screening (CS) and gross emitter identification (GEI).

- Based on track data, measurement interferences from following a preceding vehicle too closely are significant for PM. Vehicle spacing criteria are needed in addition to the normal internal validation criteria for the RSD measurements.
- Based on track data, the DRI UV backscatter system is very sensitive to blue smoke, but insensitive to dense black smoke. The ESP IR system is very sensitive to black smoke, but insensitive to blue smoke. The ESP UV system was moderately responsive to both types of smoke.
- The on-road data show very little correlation among the three RSD methods for PM over thousands of records. That lack of correlation means there is no on-road verification that the systems are working correctly.
- For on-road data, each RSD system produced a distribution of PM measurements concentrated near or below zero with a relatively small percentage of high PM measurements. Each distribution looks reasonable on its own. The lack of correlation could be due to each system capturing the vehicles at a different location on the on-ramp, or due to noise and interference problems. In the absence of correlation, the only way to determine if the systems are correctly identifying high PM emitters is to bring in a selection of vehicles flagged as high PM for mass measurement testing.
- Based on the sensitivity of the ESP UV system to both blue and black smoke, and based on the much simpler logistics involved in setting up and operating the ESP UV system compared with the DRI system, we consider the ESP UV system to be the best candidate for further evaluation in a program with a wider deployment of RSD systems.

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Appendix

Appendix A1. Gas Emissions of the Test Vehicles

Vehicle 1: 97 Ford Escort

Test ID	I0607013	I0607015	Diff..
Unit	g/mi	g/mi	% of mean
HC+NOx	0.240	0.174	32%
THC	0.114	0.061	61%
CH_4	0.003	0.003	0%
NMHC	0.110	0.058	62%
NOx	0.126	0.112	12%
CO	0.767	0.809	5%
CO_2	324.140	314.638	3%

Vehicle 5: 95 Dodge Dakota

Test ID	I0607012	I0607017	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	20.373	32.236	45%
THC	19.797	32.030	47%
CH_4	1.625	3.175	65%
NMHC	18.196	28.900	45%
NOx	0.575	0.206	94%
CO	124.289	129.247	4%
CO_2	256.250	240.365	6%

Vehicle 2: 1985 Toyota Camry

Test ID	I0607002	I0607006	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	2.414	2.465	2%
THC	1.059	1.089	3%
CH_4	0.107	0.106	1%
NMHC	0.937	0.968	3%
NOx	1.354	1.376	2%
CO	11.066	10.252	8%
CO_2	331.080	331.178	0%

Vehicle 6: 1963 Studebaker Avanti

Test ID	I0607019	I0607020	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	20.571	21.536	5%
THC	19.883	20.599	4%
CH_4	1.819	1.610	12%
NMHC	18.090	19.012	5%
NOx	0.688	0.937	31%
CO	126.811	149.308	16%
CO_2	366.238	381.038	4%

Vehicle 3: 1991 GMC Sonoma

Test ID	I0607007	I0607010	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	1.476	1.533	4%
THC	0.517	0.582	12%
CH_4	0.065	0.070	7%
NMHC	0.443	0.501	12%
NOx	0.959	0.951	1%
CO	11.330	12.204	7%
CO_2	500.277	505.634	1%

Vehicle 7: 1998 Toyota Camry

Test ID	I0607008	I0607009	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	9.491	9.920	4%
THC	9.117	9.539	5%
CH_4	0.960	0.985	3%
NMHC	8.022	8.416	5%
NOx	0.374	0.381	2%
CO	96.079	97.021	1%
CO_2	341.576	345.009	1%

Vehicle 4: 1981 Toyota Truck

Test ID	I0607018	I0607021	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	15.102	similar	
THC	9.869	similar	
CH_4	0.562	similar	
NMHC	9.316	similar	
NOx	5.233	similar	
CO	42.584	similar	
CO_2	344.630	similar	

Vehicle 8: 1986 Mitsubishi Mighty Max

Test ID	I0607004	I0607005	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	3.159	4.893	43%
THC	1.745	4.048	80%
CH_4	0.221	0.418	62%
NMHC	1.493	3.571	82%
NOx	1.414	0.845	50%
CO	28.498	50.313	55%
CO_2	411.112	378.570	8%

Appendix A2. Gas Emissions of the Repaired and Unrepaired Vehicles

Vehicle 1: 97 Ford Escort

Test ID	070717_1445	070718_1000	Diff..
Unit	g/mi	g/mi	% of mean
HC+NOx	0.285	0.243	16%
THC	0.071	0.061	14%
CH_4	0.004	0.003	17%
NMHC	0.063	0.055	14%
NOx	0.222	0.188	16%
CO	1.028	0.610	51%
CO_2	322.509	331.512	3%

Vehicle 2: 1985 Toyota Camry

Test ID	070717_1316	070718_1120	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	3.048	3.320	9%
THC	1.767	1.982	11%
CH_4	0.182	0.202	10%
NMHC	1.488	1.672	12%
NOx	1.560	1.648	5%
CO	19.946	17.804	11%
CO_2	336.490	365.746	8%

Vehicle 3: 1991 GMC Sonoma

Test ID			Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx			
THC			
CH_4			
NMHC			
NOx			
CO			
CO_2			

Vehicle 4: 1981 Toyota Truck

Test ID	070718_1307		Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	15.375		
THC	11.392		
CH_4	0.538		
NMHC	10.223		
NOx	5.152		
CO	42.783		
CO_2	336.561		

Vehicle 5: 95 Dodge Dakota

Test ID	070719_0851	070720_0934	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	3.181	3.525	10%
THC	2.376	2.565	8%
CH_4	0.180	0.201	11%
NMHC	2.066	2.223	7%
NOx	1.115	1.302	15%
CO	31.107	39.346	23%
CO_2	424.027	454.914	7%

Vehicle 6: 1963 Studebaker Avanti

Test ID			Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx			
THC			
CH_4			
NMHC			
NOx			
CO			
CO_2			

Vehicle 7: 1998 Toyota Camry

Test ID	070719_1017	070720_1100	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	0.298	0.291	2%
THC	0.121	0.099	20%
CH_4	0.015	0.012	20%
NMHC	0.100	0.081	21%
NOx	0.198	0.210	6%
CO	2.739	1.622	51%
CO_2	398.328	393.934	1%

Vehicle 8: 1986 Mitsubishi Mighty Max

Test ID	070814_1221	070816_1143	Diff.
Unit	g/mi	g/mi	% of mean
HC+NOx	4.166	4.059	3%
THC	2.802	2.912	4%
CH_4	0.304	0.333	9%
NMHC	2.345	2.420	3%
NOx	1.821	1.639	10%
CO	35.041	37.055	6%
CO_2	452.004	466.212	3%

Appendix A3. Change in Gas Emissions of the Repaired and Unrepaired Vehicles

Vehicle 1: 97 Ford Escort						**Vehicle 5: 95 Dodge Dakota**				
Test ID	original	new	change	change		Test ID	original	new	change	change
Unit	g/mi	g/mi	g/mi	% of orig		Unit	g/mi	g/mi	g/mi	% of orig
HC+NOx	0.21	0.26	0.06	28%		HC+NOx	16.34	1.81	-14.53	-89%
THC	0.09	0.07	-0.02	-25%		THC	16.25	1.32	-14.93	-92%
CH_4	0.00	0.00	0.00	17%		CH_4	1.91	0.16	-1.76	-92%
NMHC	0.08	0.06	-0.03	-30%		NMHC	14.68	1.15	-13.53	-92%
NOx	0.12	0.21	0.09	72%		NOx	0.57	0.73	0.15	27%
CO	0.79	0.82	0.03	4%		CO	64.64	19.79	-44.86	-69%
CO_2	319.39	327.01	7.62	2%		CO_2	120.21	227.49	107.28	89%
Vehicle 2: 1985 Toyota Camry						**Vehicle 6: 1963 Studebaker Avanti**				
Test ID	original	new	change	change		Test ID	original	new	change	change
Unit	g/mi	g/mi	g/mi	% of orig		Unit	g/mi	g/mi	g/mi	% of orig
HC+NOx	2.44	3.18	0.74	31%		HC+NOx	10.79			
THC	1.07	1.87	0.80	75%		THC	10.32			
CH_4	0.11	0.19	0.09	80%		CH_4	0.87			
NMHC	0.95	1.58	0.63	66%		NMHC	9.53			
NOx	1.37	1.60	0.24	18%		NOx	0.62			
CO	10.66	18.88	8.22	77%		CO	74.73			
CO_2	331.13	351.12	19.99	6%		CO_2	190.54			
Vehicle 3: 1991 GMC Sonoma						**Vehicle 7: 1998 Toyota Camry**				
Test ID	original	new	change	change		Test ID	original	new	change	change
Unit	g/mi	g/mi	g/mi	% of orig		Unit	g/mi	g/mi	g/mi	% of orig
HC+NOx	1.50					HC+NOx	4.98	0.16	-4.82	-97%
THC	0.55					THC	4.79	0.15	-4.65	-97%
CH_4	0.07					CH_4	0.51	0.11	-0.40	-79%
NMHC	0.47					NMHC	4.23	0.15	-4.09	-97%
NOx	0.96					NOx	0.20	0.14	-0.07	-33%
CO	11.77					CO	48.52	1.07	-47.45	-98%
CO_2	502.96					CO_2	172.51	196.97	24.46	14%
Vehicle 4: 1981 Toyota Truck						**Vehicle 8: 1986 Mitsubishi Mighty Max**				
Test ID	original	new	change	change		Test ID	original	new	change	change
Unit	g/mi	g/mi	g/mi	% of orig		Unit	g/mi	g/mi	g/mi	% of orig
HC+NOx	15.10	15.38	0.27	2%		HC+NOx	2.66	2.04	-0.62	-23%
THC	9.87	11.39	1.52	15%		THC	2.42	1.48	-0.95	-39%
CH_4	0.56	0.54	-0.02	-4%		CH_4	0.52	0.21	-0.31	-59%
NMHC	9.32	10.22	0.91	10%		NMHC	2.20	1.23	-0.97	-44%
NOx	5.23	5.15	-0.08	-2%		NOx	0.67	0.87	0.20	29%
CO	42.58	42.78	0.20	0%		CO	25.43	18.56	-6.87	-27%
CO_2	344.63	336.56	-8.07	-2%		CO_2	189.33	233.12	43.80	23%

Appendix B. Tests exceeding the Range of Gas Analyzers for the UC Cycle

Vehicle	Test ID	Phase	Pollutant	Range Limit (mg/mi)	Measured (mg/mi)	Over the Range Percentage
4	I0607018	1	CH_4	0.782	5.639	621%
			THC	21.380	119.994	461%
			CO	148.157	204.101	38%
	I0607021	1	CH_4	0.796	5.635	608%
			THC	21.496	136.298	534%
			CO	149.515	205.552	37%
5	I0607012	1	CH_4	0.838	4.915	487%
			THC	38.452	147.568	284%
			CO	264.276	386.424	46%
		2	CH_4	0.407	1.376	238%
			THC	11.229	15.560	39%
			CO	76.484	112.000	46%
		3	CH_4	0.783	2.432	210%
			THC	21.739	24.479	13%
			CO	148.045	203.507	37%
6	I0607019	1	CH_4	0.866	2.939	239%
			THC	3.049	4.721	55%
			CO	162.515	230.791	42%
		2	CH_4	0.395	1.719	335%
			THC	10.777	18.381	71%
			CO	73.817	114.081	55%
		3	CH_4	0.794	2.304	190%
			THC	21.695	26.961	24%
			CO	148.362	215.298	45%
	I0607020	1	CH_4	0.796	2.719	242%
			THC	21.187	34.040	61%
			CO	149.121	214.781	44%
		2	CH_4	0.491	1.460	197%
			THC	12.922	18.992	47%
			CO	92.036	138.213	50%
		3	CH_4	0.778	2.331	200%
			THC	20.759	27.165	31%
			CO	146.641	215.272	47%
7	I0607008	1	CH4	0.692	2.401	247%
			THC	22.023	22.436	2%
			CO	149.288	184.693	24%
		2	CH4	0.352	0.824	134%
			CO	75.900	86.787	14%
		3	CH4	0.731	1.601	119%
			CO	136.886	146.900	7%
	I0607009	1	CH4	0.695	2.513	262%
			THC	22.327	23.090	3%
			CO	151.397	189.150	25%
		2	CH4	0.353	0.842	138%
			CO	76.810	87.519	14%
		3	CH4	0.682	1.648	142%
8	I0607004	1	CH4	0.690	0.732	6%
			CO	148.869	158.165	6%
	I0607005	1	CH4	0.696	2.856	310%
			THC	22.268	29.595	33%
			CO	151.067	213.294	41%

Appendix C1. Particulate Mass and Number Emissions for Each Test

Vehicle	Test ID	Phase	DustTrak (mg/mi)	Filter (mg/mi)	CPC (particles/mi)	Dilution for CPC
1	I0607013	1	0.860	5.742	6.222E+12	w/ dilution
		2	0.322	2.213	4.066E+12	
		3	0.327	0.832	4.069E+12	
		weighted	0.350	2.301	4.178E+12	
	I0607014*	1	0.421		1.416E+12	w/o dilution
		2	0.338		2.265E+13	
		3	0.454		2.859E+12	
		weighted	0.350		2.017E+13	
	I0607015	1	1.468	-0.719	1.077E+13	w/o dilution
		2	0.307	0.682	4.603E+12	
		3	0.244	2.263	2.350E+12	
		weighted	0.363	0.718	4.768E+12	
	I0607016*	1	0.289		1.153E+12	w/o dilution
		2	0.263		1.151E+13	
		3	0.305		2.648E+12	
		weighted	0.267		1.035E+13	
2	I0607002	1	6.860	16.317	7.759E+13	w/o dilution
		2	19.020	35.364	7.517E+13	
		3	17.275	26.742	8.748E+13	
		weighted	18.266	33.775	7.615E+13	
	I0607006	1	5.731	17.874	8.659E+13	w/o dilution
		2	4.153	15.378	7.968E+13	
		3	15.445	32.869	9.424E+13	
		weighted	5.014	16.714	8.104E+13	
3	I0607007	1	31.388	35.473	1.381E+14	w/o dilution
		2	0.359	8.160	8.884E+13	
		3	0.140	-0.927	4.989E+12	
		weighted	1.960	8.956	8.563E+13	
	I0607010	1	37.430	43.349	1.361E+14	w/ dilution
		2	0.364	2.810	9.364E+13	
		3	0.730	-2.275	2.045E+12	
		weighted	2.313	4.565	8.954E+13	
4	I0607018	1	2102.587	1381.139	2.443E+14	w/ dilution
		2	299.452	668.902	2.534E+14	
		3	189.808	2941.117	1.356E+14	
		weighted	386.490	863.157	2.448E+14	
	I0607021	1	1381.798	1091.875	1.779E+14	w/ dilution
		2	833.418	292.876	1.929E+13	
		3	N/A	N/A	N/A	
		weighted	N/A	N/A	N/A	

*: Warm start test, no filters were collected.

Appendix C1. Particulate Mass and Number Emissions for Each Test (Continued)

Vehicle	Test ID	Phase	DustTrak (mg/mi)	Filter (mg/mi)	CPC (particles/mi)	Dilution for CPC
5	I0607012	1	545.947	1135.451	2.476E+14	w/ dilution
		2	79.037	92.318	1.966E+14	
		3	99.297	109.326	6.489E+13	
		weighted	103.558	145.150	1.900E+14	
	I0607017	1	418.739	594.381	2.139E+14	w/ dilution
		2	182.219	272.814	1.874E+14	
		3	230.158	233.328	5.410E+13	
		weighted	198.044	286.991	1.794E+14	
6	I0607019	1	2475.794	1493.544	5.247E+14	w/ dilution
		2	2947.201	3134.592	5.898E+14	
		3	848.462	653.560	4.701E+14	
		weighted	2779.109	2883.003	5.783E+14	
	I0607020	1	728.501	579.899	4.708E+14	w/ dilution
		2	781.973	563.092	5.774E+14	
		3	413.575	432.498	4.276E+14	
		weighted	748.454	553.423	5.586E+14	
7	I0607008	1	80.815	140.220	1.744E+14	w/o dilution
		2	36.372	53.432	8.881E+13	
		3	35.941	59.875	1.185E+14	
		weighted	38.660	58.403	9.532E+13	
	I0607009	1	85.629	153.350	1.324E+14	w/ dilution
		2	38.881	57.852	1.737E+14	
		3	29.061	51.188	8.606E+13	
		weighted	40.636	62.363	1.655E+14	
8	I0607004	1	171.400	201.217	1.618E+14	w/o dilution
		2	34.856	74.497	1.007E+14	
		3	20.978	24.767	3.907E+13	
		weighted	40.973	77.630	9.965E+13	
	I0607005	1	306.156	337.250	1.966E+14	w/o dilution
		2	34.240	49.906	7.698E+13	
		3	19.943	2.760	5.308E+13	
		weighted	47.389	61.580	8.155E+13	

Appendix D. Impact of AC Use on Emissions

Bag	Measured	Cold Start (w/o AC)		Warm Start (Max AC)		w/ AC Diff. from w/o AC	Warm Start Bag 1 Diff. from Bag 3
		I0607013	I0607015	I0607014	I0607016		
1	HC+NO_X (g)	1.638	1.382	0.686	0.593		142%
	THC (g)	1.167	0.878	0.252	0.122		278%
	CH_4 (g)	0.047	0.042	0.017	0.015		129%
	NMHC (g)	1.121	0.836	0.235	0.107		302%
	NO_X (g)	0.471	0.504	0.434	0.471		111%
	CO (g)	4.824	4.178	0.623	0.179		54%
	CO_2 (g)	615.689	610.300	629.856	608.729		2%
	PM (mg)	1.022	1.744	0.500	0.343		-7%
	PN (#)	7.39E+12	1.28E+13	1.7E+12	1.4E+12		-54%
	FE (mpg)	16.222	16.358	16.103	16.676		-2%
2	HC+NO_X (g)	1.537	1.027	1.517	1.432	15%	
	THC (g)	0.551	0.198	0.294	0.144	-42%	
	CH_4 (g)	0.010	0.012	0.026	0.023	123%	
	NMHC(g)	0.541	0.186	0.267	0.122	-46%	
	NO_X (g)	0.986	0.829	1.222	1.287	38%	
	CO (g)	5.307	5.942	16.748	9.286	131%	
	CO_2 (g)	2650.511	2560.872	3343.463	3181.573	25%	
	PM (mg)	2.772	2.641	2.909	2.264	-4%	
	PN (#)	3.50E+13	3.96E+13	2E+14	9.9E+13	294%	
	FE (mpg)	27.732	28.694	21.890	23.061	-26%	
3	HC+NO_X (g)	0.193	0.137	0.336	0.192	60%	
	THC (g)	0.108	0.046	0.065	0.034	-36%	
	CH_4 (g)	0.006	0.007	0.007	0.007	8%	
	NMHC (g)	0.101	0.040	0.058	0.027	-40%	
	NO_X (g)	0.085	0.091	0.270	0.158	143%	
	CO (g)	0.230	0.325	0.361	0.161	-6%	
	CO_2 (g)	458.904	452.598	618.839	595.379	33%	
	PM (mg)	0.390	0.291	0.541	0.363	33%	
	PN (#)	4.85E+12	2.8E+12	3.4E+12	3.2E+12	-14%	
	FE (mpg)	22.220	22.402	16.484	17.030	-34%	

PN: Particle Number; FE: Fuel Economy.

Appendix E. Smog Check Data of the Test Vehicles

Vehicle	Date	Test Mode	RPM	CO2 (%)	O2 (%)	HC (ppm)			CO (%)			NO (ppm)			Result
			MEAS	MEAS	MEAS	MAX	AVE/GP	MEAS	MAX	AVE/GP	MEAS	MAX	AVE/GP	MEAS	
1	7/24/2006	ASM5015	**1831**	**14**	**0.2**	64	9	**14**	0.55	0.02	**0.01**	477	57	**221**	**Pass**
		ASM2525	**1691**	**14**	**0.2**	47	7	**9**	0.54	0.03	**0.00**	764	50	**210**	**Pass**
	7/20/2006	ASM5015	**1811**	**14.1**	**0.3**	64	9	**16**	0.55	0.02	**0.03**	477	57	**197**	**Pass**
		ASM2525	**1788**	**14.1**	**0.2**	47	7	**11**	0.54	0.03	**0.00**	764	50	**193**	**Pass**
2	7/8/2006	ASM5015	**1628**	**13.7**	**0.6**	144	41	**144**	0.88	0.13	**0.39**	1175	399	**1100**	**Pass**
		ASM2525	**1697**	**13.9**	**0.3**	120	29	**107**	0.68	0.11	**0.44**	1005	332	**769**	**Pass**
	7/17/2006	ASM5015	**1605**	**13.8**	**0.6**	144	41	**143**	0.88	0.13	**0.36**	1175	399	**880**	**Pass**
		ASM2525	**2653**	**14.1**	**0.2**	120	29	**70**	0.68	0.11	**0.30**	1005	332	**581**	**Pass**
3	7/12/2006	ASM5015	**1424**	**12.5**	**2.4**	123	34	**123**	0.73	0.11	**0.45**	1015	260	**321**	**Pass**
		ASM2525	**1362**	**12.4**	**2.6**	103	23	**70**	0.93	0.1	**0.32**	875	217	**222**	**Pass**
	7/21/2006	ASM5015	**1416**	**11.8**	**2.4**	123	34	**155**	0.73	0.11	**0.57**	1015	260	**601**	**Fail**
		ASM2525	**1376**	**11.9**	**2.4**	103	23	**75**	0.93	0.1	**0.28**	875	217	**360**	**Pass**
4	7/24/2006	ASM5015	**2598**	**12.7**	**0.7**	218	49	**2332**	1.58	0.24	**1.32**	1523	535	**2014**	**Fail**
		ASM2525	**2592**	**13.1**	**0.8**	132	38	**177**	1.38	0.23	**0.66**	1383	449	**1817**	**Fail**
	7/26/2006	ASM5015	**2541**	**12.6**	**1.4**	218	49	**125**	1.58	0.24	**0.27**	1523	535	**2290**	**Fail**
		ASM2525	**2597**	**12.7**	**1.1**	132	38	**124**	1.38	0.23	**0.36**	1383	449	**1980**	**Fail**
6	7/26/2006	ASM5015	**1913**	**7.6**	**0.2**	344	544	**497**	3.67	5.37	**10.80**	1600	3085	**307**	**GP**
		ASM2525	**2228**	**7.5**	**0.2**	294	494	**476**	3.47	5.17	**11.09**	1460	2885	**307**	**GP**
	7/26/2006	ASM5015	**1944**	**7.7**	**0.2**	344	544	**477**	3.67	5.37	**10.75**	1600	3085	**246**	**GP**
		ASM2525	**2292**	**7.5**	**0.2**	294	494	**482**	3.47	5.17	**11.06**	1460	2885	**245**	**GP**
7	7/11/2006[L]	ASM5015	**1749**	**10.7**	**0.2**	52	270	**632**	0.49	1.99	**6.46**	424	1912	**201**	**GP**
		ASM2525	**1733**	**7.5**	**0.2**	36	220	**884**	0.46	1.96	**11.29**	711	1712	**118**	**GP**
	7/21/2006[R]	ASM5015	**1739**	**10.2**	**0.2**	52	270	**550**	0.49	1.99	**6.49**	424	1912	**363**	**GP**
		ASM2525	**1736**	**6.6**	**0.2**	36	220	**821**	0.46	1.96	**12.16**	711	1712	**231**	**GP**
8	7/7/2006	ASM5015	**1913**	**14.1**	**0.1**	143	43	**142**	1.01	0.16	**0.94**	1128	406	**251**	**Pass**
		ASM2525	**1948**	**14.1**	**0.0**	115	32	**115**	1.28	0.15	**1.03**	1205	349	**182**	**Pass**
	7/17/2006	ASM5015	**1906**	**13.3**	**0.1**	143	43	**184**	1.01	0.16	**1.85**	1128	406	**295**	**Fail**
		ASM2525	**1989**	**13.4**	**0.0**	115	32	**156**	1.28	0.15	**1.82**	1205	349	**242**	**Fail**

MAX = Maximum Allowed Emissions; AVE = Average Emissions for Passing Vehicles; MEAS = Amount Measured; GP = Gross Polluter
The test for vehicle 5 could not succeed because the HC emission was over the range of the gas analyzer. [L]: Measured from the left side tailpipe; [R]: Measured from the right side tailpipe. Data marked in red were the pollutants which were over MAX.

Appendix F. PM Emission Rates Measured with Tailpip Screening Device (mg/sec)

Vehicle	Date	Ambient	Idle	High Speed Idle	ASM5015	ASM2525
1	7/20/2006	0.005	0.006		0.006	0.006
	7/24/2006	0.005	0.005	0.004	0.010	0.019
2	7/08/2006				13.607	24.785
	717/2006		0.334		2.157	10.013
3	7/12/2006	0.002	0.002		0.003	0.010
	7/21/2006		0.003	0.002	0.007	0.004
4	7/24/2006	0.008	0.609	1.046	4.573	5.926
	7/26/2006	0.042	0.301	0.414	0.259	0.225
5	7/20/2006	0.007	0.032		0.496	0.116
6	7/26/2006	0.006	0.021	1.530	0.529	1.415
	7/26/2006		0.070	3.304	3.107	5.873
7	7/11/2006	0.004	0.006	0.028	0.127	0.283
	7/21/2006		0.032		0.101	0.268
8	7/07/2006	0.004	0.050	0.074	1.070	0.165
	7/17/2006				1.389	0.251

Appendix G. Remote Sensing Results (HC, g/kg fuel)

RSD	Date	Vehicle	Starting Distance (feet)					
			25	50	75	100	150	200
ESP	7/25/06	1	0.528	0.374	0.656	0.458	0.741	1.144
		2	4.611	2.886	2.464	2.540	2.928	2.829
		3	2.480	1.641	1.332	1.205	1.499	1.336
		4	6.506	5.976	7.481	4.212	15.599	4.148
		5	318.441					
		6	22.260	17.504	19.726	13.852	12.422	24.694
		7	5.241	4.266	4.568	7.259	5.273	3.707
		8	5.636	4.875	9.519	8.757	6.944	9.597
	7/26/06	1	0.332	0.010	0.034	0.095	-0.006	0.043
		2	4.715	2.799	2.417	2.642	2.180	2.217
		3	2.292	1.908	1.023	1.099	0.857	0.580
		4	490.227	3.882	3.333	3.184	9.140	2.483
		5	4.903					
		6	30.144	26.357	23.095	18.692	14.509	13.206
		7	4.148	2.889	2.306	2.628	2.422	3.499
DRI	7/25/06	1	1.036	0.262	0.220	0.364	2.507	0.838
		2	12.341	6.083	5.702	6.899	7.719	7.400
		3	6.740	3.542	3.504	2.487	3.264	
		4	8.245	8.369	15.112	7.017	6.334	13.445
		6	28.058		26.514	26.434	23.103	
		7	13.135	9.421	9.868		12.484	6.111
		8	12.286	8.557	18.330	5.404	2.397	2.670
	7/26/06	1	0.416	0.221	0.396	0.560	0.658	0.176
		2	13.244	7.077	6.644	6.549	5.461	5.827
		3	6.556	6.224	2.988	3.628	1.347	2.106
		6	29.910	32.412	30.075	27.034	23.930	25.133
		8	12.486	9.818	7.804	6.607	8.217	5.353

Appendix H. Remote Sensing Results (CO, g/kg fuel)

RSD	Date	Vehicle	Starting Distance (feet)					
			25	50	75	100	150	200
ESP	7/25/06	1	4.320	197.597	266.051	221.607	342.226	360.209
		2	570.932	614.266	431.853	578.984	665.980	663.129
		3	687.898	730.164	641.225	495.924	672.113	706.397
		4	184.258	215.355	290.502	452.157	358.432	240.380
		5	1155.587					
		6	753.945	805.871	837.728	909.681	1002.176	886.467
		7	576.822	625.345	717.685	1102.580	956.501	1015.778
		8	595.557	448.529	314.747	373.901	178.034	184.395
	7/26/06	1	29.695	93.422	169.125	198.317	333.766	256.677
		2	521.967	507.716	475.713	612.301	491.066	598.012
		3	464.004	540.651	397.912	360.128	413.775	322.365
		4	492.167	645.261	233.644	345.132	296.629	282.824
		5	986.288					
		6	518.856	844.040	987.003	1006.089	1071.123	1062.768
		7	455.647	632.274	875.524	1092.404	1112.251	1149.216
DRI	7/25/06	1	2.646	185.040	213.938	179.287	293.999	283.999
		2	528.859	522.874	403.804	524.140	607.106	628.773
		3	656.974	678.782	627.287	427.489	637.033	
		4	62.343	35.288	2673.334	428.331	396.151	191.612
		6	676.572	821.028	724.838	736.986	766.857	
		7	433.695	505.045	588.110		564.642	632.377
		8	484.055	418.997	231.586	348.466	86.294	162.432
	7/26/06	1	14.203	80.363	119.427	160.953	290.990	220.138
		2	420.993	444.702	422.654	516.796	442.048	505.109
		3	340.719	442.712	300.757	248.829	425.572	383.002
		6	394.687	662.383	834.374	763.886	798.098	805.238
		8	417.330	612.162	177.346	315.931	233.002	232.057

Appendix I. Remote Sensing Results (NO_x, g/kg fuel)

RSD	Date	Vehicle	Starting Distance (feet)					
			25	50	75	100	150	200
ESP	7/25/06	1	10.988	0.885	0.523	0.814	1.184	2.062
		2	22.249	15.026	16.302	9.962	10.888	8.993
		3	11.536	6.560	8.948	10.796	5.271	5.090
		4	66.019	62.504	47.878	45.619	62.788	67.989
		5	114.257					
		6	22.076	23.398	27.439	21.810	18.530	20.652
		7	9.107	8.210	5.509	2.128	3.250	2.960
		8	19.314	15.709	21.459	15.981	16.743	24.780
	7/26/06	1	13.584	0.349	0.723	0.787	0.923	2.231
		2	21.814	19.151	13.976	10.728	11.624	9.994
		3	17.642	14.260	19.061	14.061	8.560	6.763
		4	18.869	8.699	13.055	12.377	15.527	17.907
		5	107.159					
		6	28.442	15.023	14.079	12.343	11.895	10.817
		7	15.978	6.591	3.515	2.193	1.743	4.087
DRI	7/25/06	1	10.880	0.003	-0.082	0.463	-0.171	-0.073
		2	9.324	6.261	8.446	3.948	4.320	3.709
		3	5.985	3.556	4.407	6.939	3.970	
		4	46.541	43.494	24.959	23.749	25.463	40.047
		6	3.290		13.146	8.927	4.178	
		7	2.910	1.700	2.409		1.421	1.925
		8	4.650	5.423	8.772	7.259	8.939	11.329
	7/26/06	1	9.264	0.205	-0.038	0.048	0.064	1.730
		2	7.889	8.378	5.945	4.132	5.715	4.113
		3	11.986	9.278	12.189	8.039	4.594	6.896
		6	5.285	2.321	1.386	1.519	1.430	1.517
		8	7.491	2.370	7.014	5.393	8.911	11.066

Appendix J. Remote Sensing Results (PM, g/kg fuel)

RSD	Date	Vehicle	Starting Distance (feet)					
			25	50	75	100	150	200
ESP UV	7/25/06	1	2.316	0.281	0.240	0.331	0.364	0.107
		2	5.228	3.782	2.057	1.888	2.328	2.151
		3	1.461	0.873	0.955	0.929	1.067	1.146
		4	7.011	9.995	3.769	3.412	5.133	2.929
		5	21.111					
		6	18.104	13.348	14.007	8.671	7.056	18.674
		7	3.702	5.335	5.271	13.119	6.003	4.961
		8	10.295	3.318	2.604	2.476	1.865	2.083
	7/26/06	1	0.229	0.238	0.239	0.296	0.512	0.676
		2	6.166	3.775	1.941	2.036	2.028	1.980
		3	1.089	1.141	0.877	0.904	0.929	1.141
		4	6.396	3.561	1.729	2.718	2.238	1.578
		5	21.893					
		6	8.632	2.936	4.039	3.519	3.258	3.916
		7	6.470	4.785	3.589	3.889	3.456	6.218
ESP IR	7/25/06	1	2.072	3.092	3.404	4.061	9.506	11.206
		2	3.978	13.524	4.833	6.646	10.564	12.483
		3	4.144	6.209	8.835	12.236	10.603	13.408
		4	19.202	45.332	6.729	11.422	15.128	11.062
		5	22.697					
		6	3.539	2.872	5.521	2.404	2.569	4.932
		7	10.597	23.834	24.192	63.287	36.630	31.279
		8	16.755	6.675	7.059	10.222	8.837	12.655
	7/26/06	1	1.379	2.714	3.658	3.352	7.472	8.041
		2	5.382	7.021	6.075	4.969	7.394	9.610
		3	4.228	6.390	8.275	10.116	14.042	19.108
		4	3.857	3.069	3.403	3.714	4.773	4.855
		5	55.007					
		6	5.410	1.024	1.491	1.362	1.912	2.448
		7	16.287	15.165	12.222	15.490	15.793	27.687
DRI	7/25/06	1	0.003	0.024	0.035	0.032	0.157	0.277
		2	0.612	0.852	1.104	0.477	0.508	0.572
		3	0.205	0.106	0.101	0.205	0.209	
		4	0.494	0.481	0.910	0.461	0.455	0.496
		6	2.522	3.247	3.904	2.129	1.582	
		7	0.152	0.226	0.090		0.129	0.861
		8	2.176	1.127	0.721	0.921	0.386	0.703
	7/26/06	1	0.025	0.060	0.042	0.072	0.134	0.169
		2	0.601	0.489	0.449	0.294	0.512	0.388
		3	0.191	0.277	0.135	0.149	0.184	0.290
		6	0.729	0.620	0.702	0.774	0.895	1.136
		8	0.670	0.756	0.381	0.664	0.320	0.388